The Need for Future Colliders

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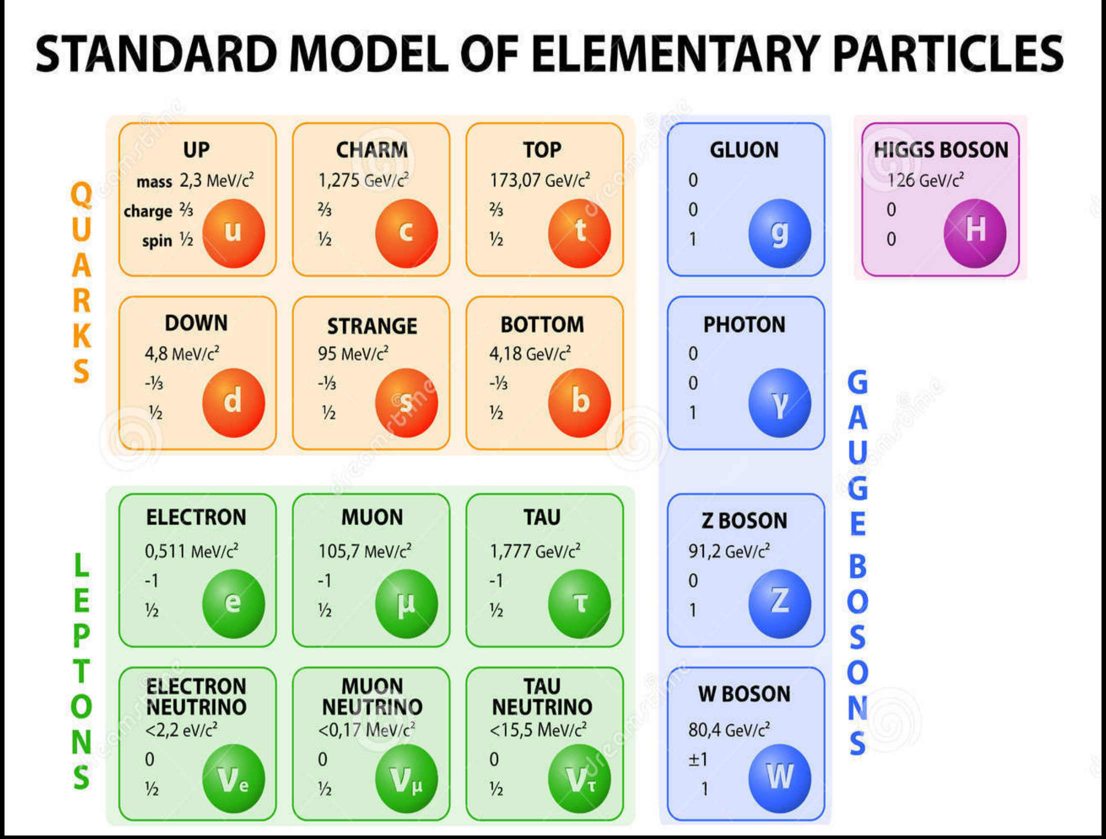
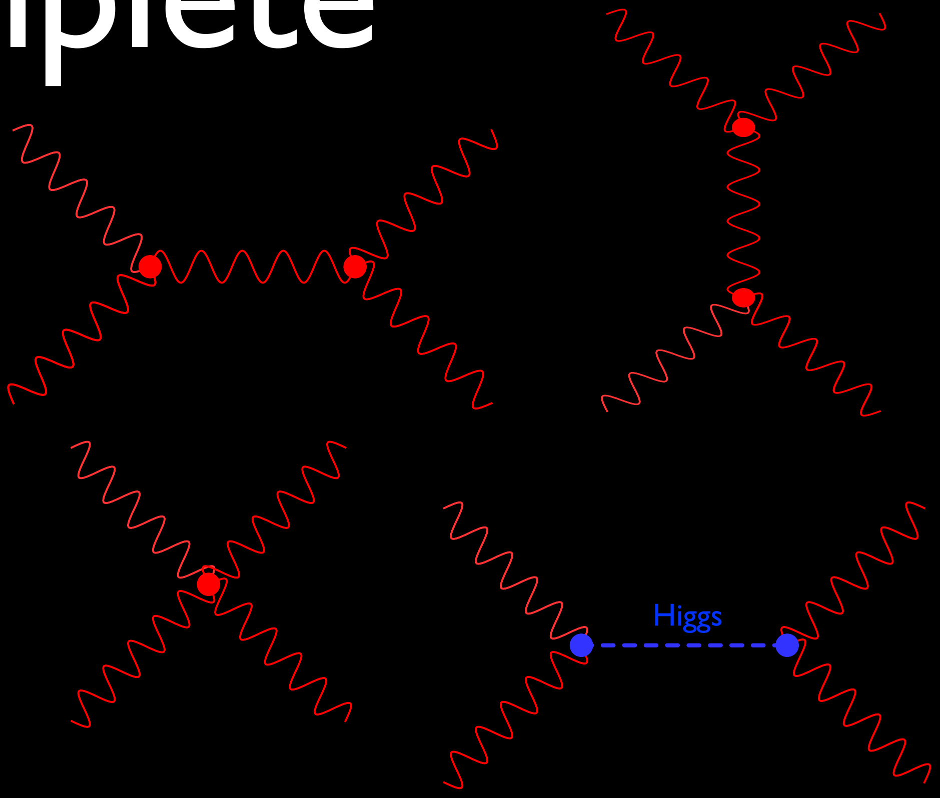
The State of the SM

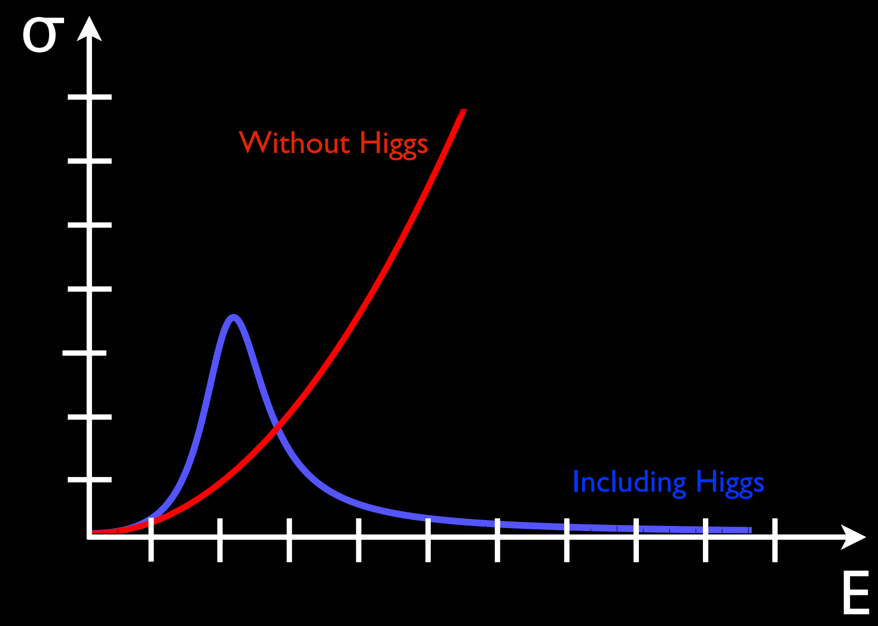
- The Higgs boson was the last missing ingredient in the Standard Model of particle physics.
- Its discovery was an amazing triumph of accelerator and detector design and operation, experimental search technique, and theoretical prediction.
- The Higgs is the remnant of the construction which preserves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



UV Complete

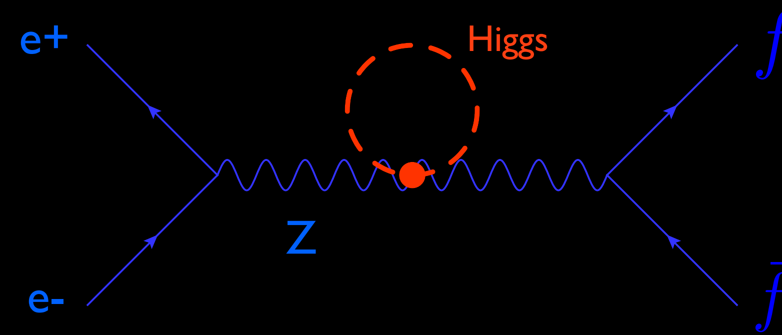
- The Higgs `UV completed' the Standard Model.
- Without it, the scattering of the weak force carriers grows with energy, and eventually becomes inconsistent with quantum mechanics because the probability of scattering ("something happening") grows larger than 100%.
- That is a clear sign that something 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.'



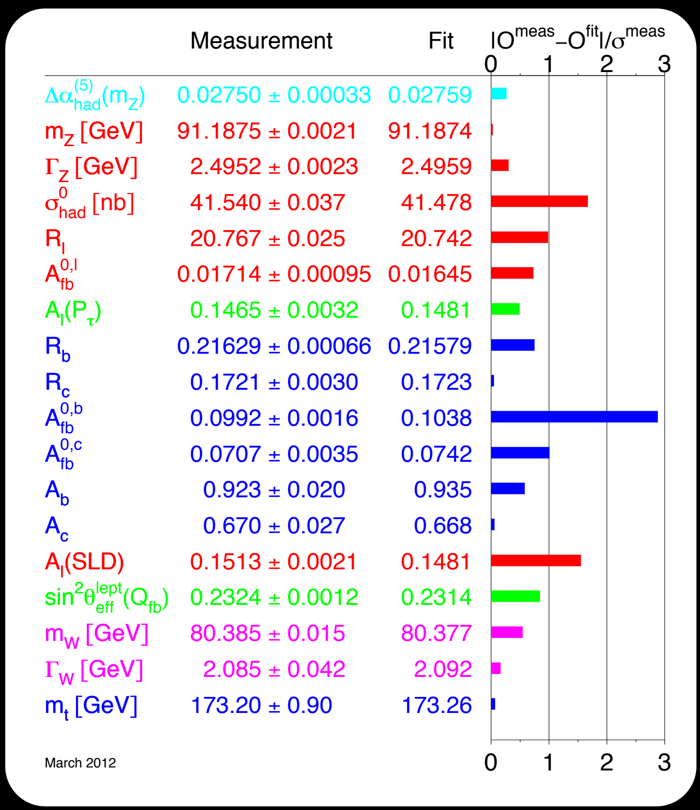


125 GeV is the right place

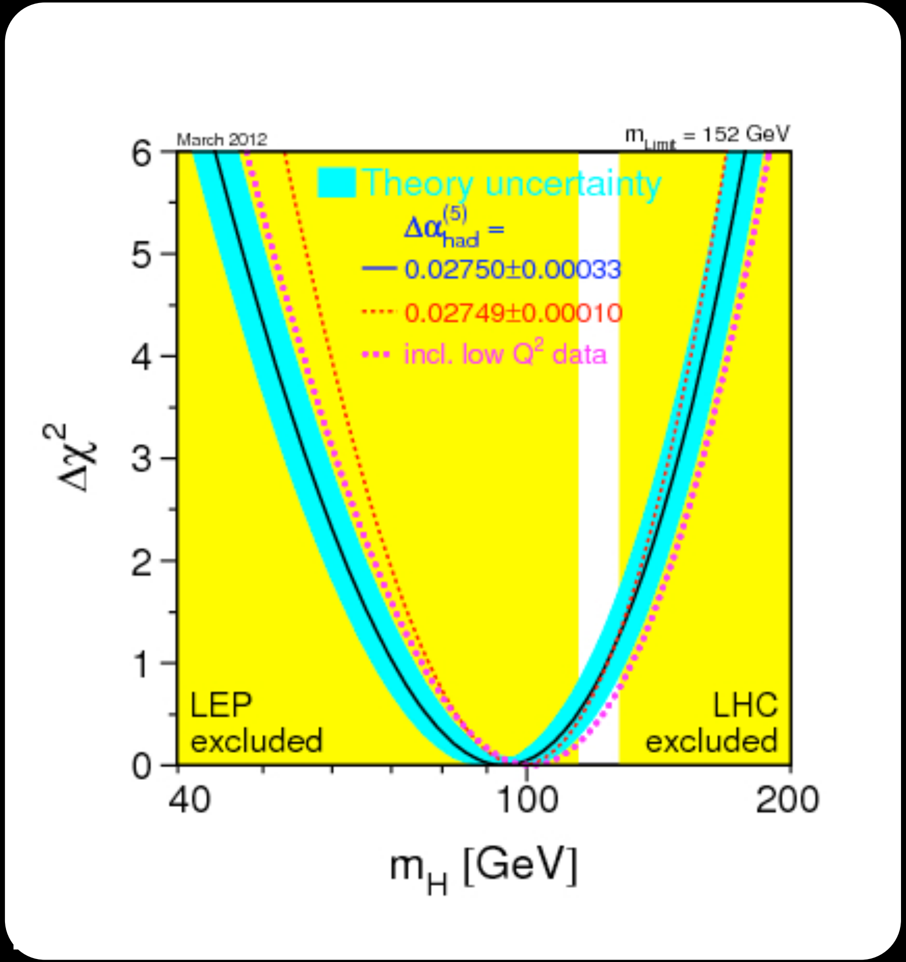
- Precision measurements of the properties of Z bosons by LEP were sensitive to virtual Higgs bosons, and as a result depended weakly on its mass.



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



	Measurement	Fit	$\vert O^{meas}-O^{fit}\vert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	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	



Too Much Success?

- The extraordinary success of the Standard Model actually makes me kind of uncomfortable.
- Up until now, we knew that there had to be something missing at the TeV energy scale, because we knew that the weak boson scattering amplitudes became too large at that energy.
    - Now we have that missing ingredient in hand. Our theories could potentially work all the way until the Planck scale (where quantum gravity becomes important).
- For the first time since we have had a modern understanding of the three fundamental forces contained in the Standard Model, we have a theory which doesn't seem to have any internal tension up to extremely high energies, well beyond the reach of our most ambitious experiments.
- Is particle physics over?

Some Historical Perspective

- The situation reminds me of a somewhat analogous chapter of history.
- 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

Aspen, Colorado

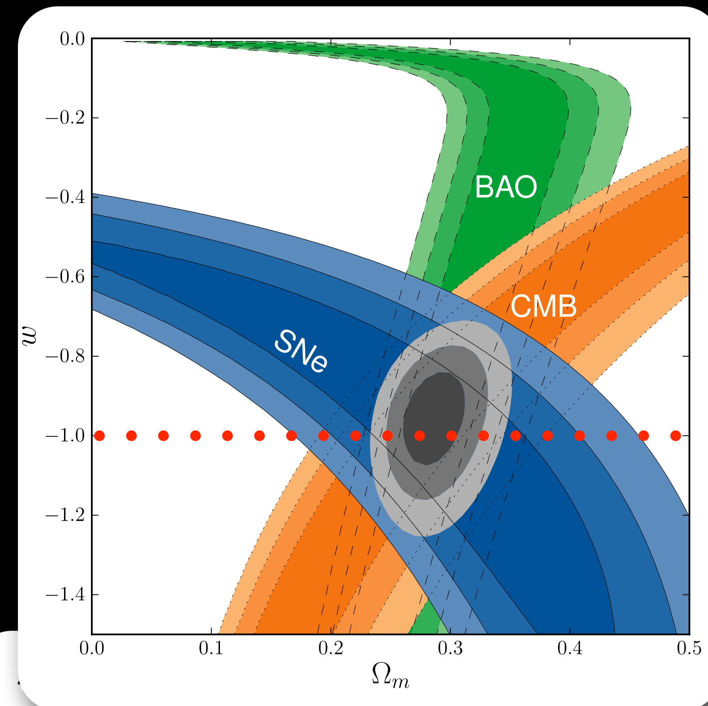
- Kelvin's two clouds were what seemed like an inconsistency in the properties of the luminiferous ether (through which EM waves supposedly propagated) and the observed spectrum of thermal radiation from a blackbody.
- Today we know that the first was a hint leading to Einstein's special relativity.
- 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.



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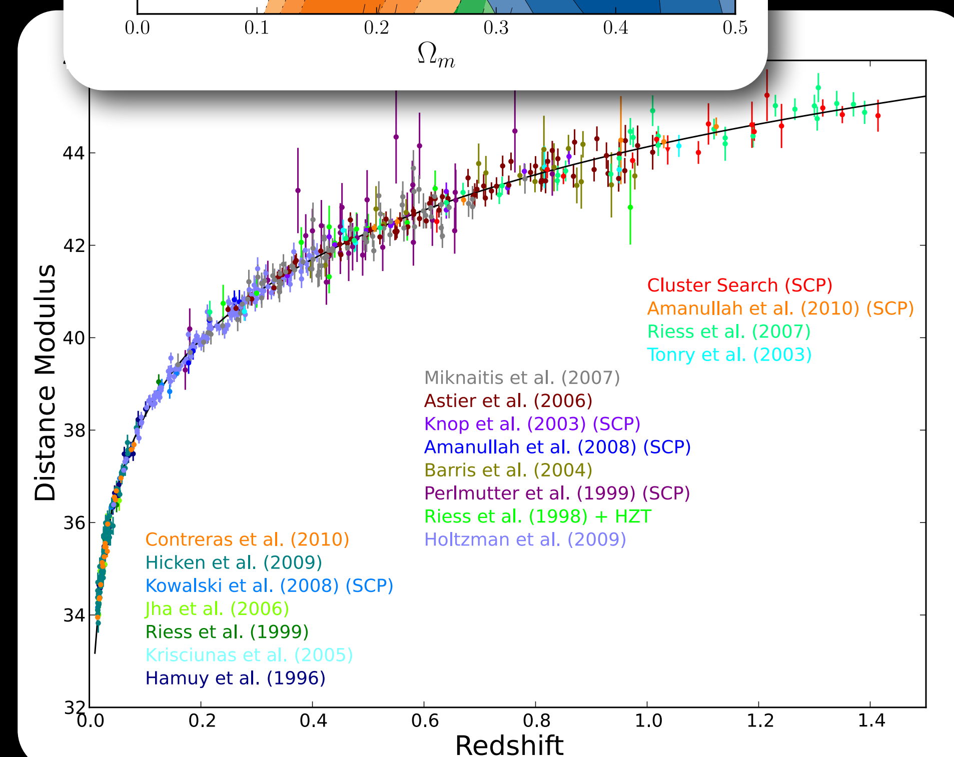

Dark Matter

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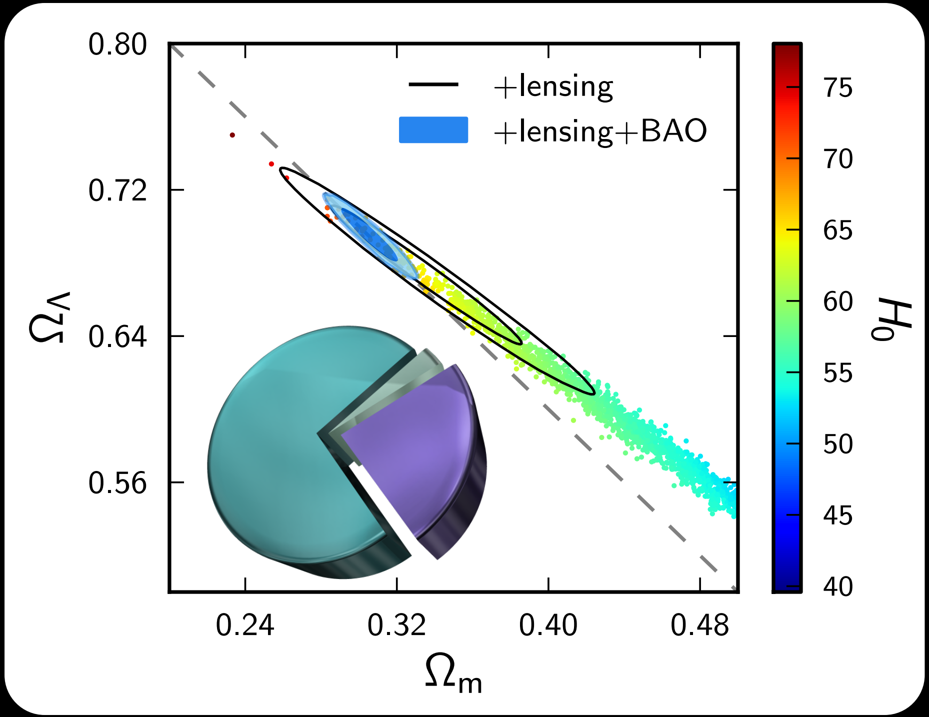
- Dark energy is not the only dark component of the Universe.
- A wide range of evidence indicates most of the matter in the Universe is some kind of non-baryonic massive particle.
  - Rotation curves/Motion in clusters
  - Power spectrum of the CMB
  - Distribution of large scale structure
- Nothing 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?!

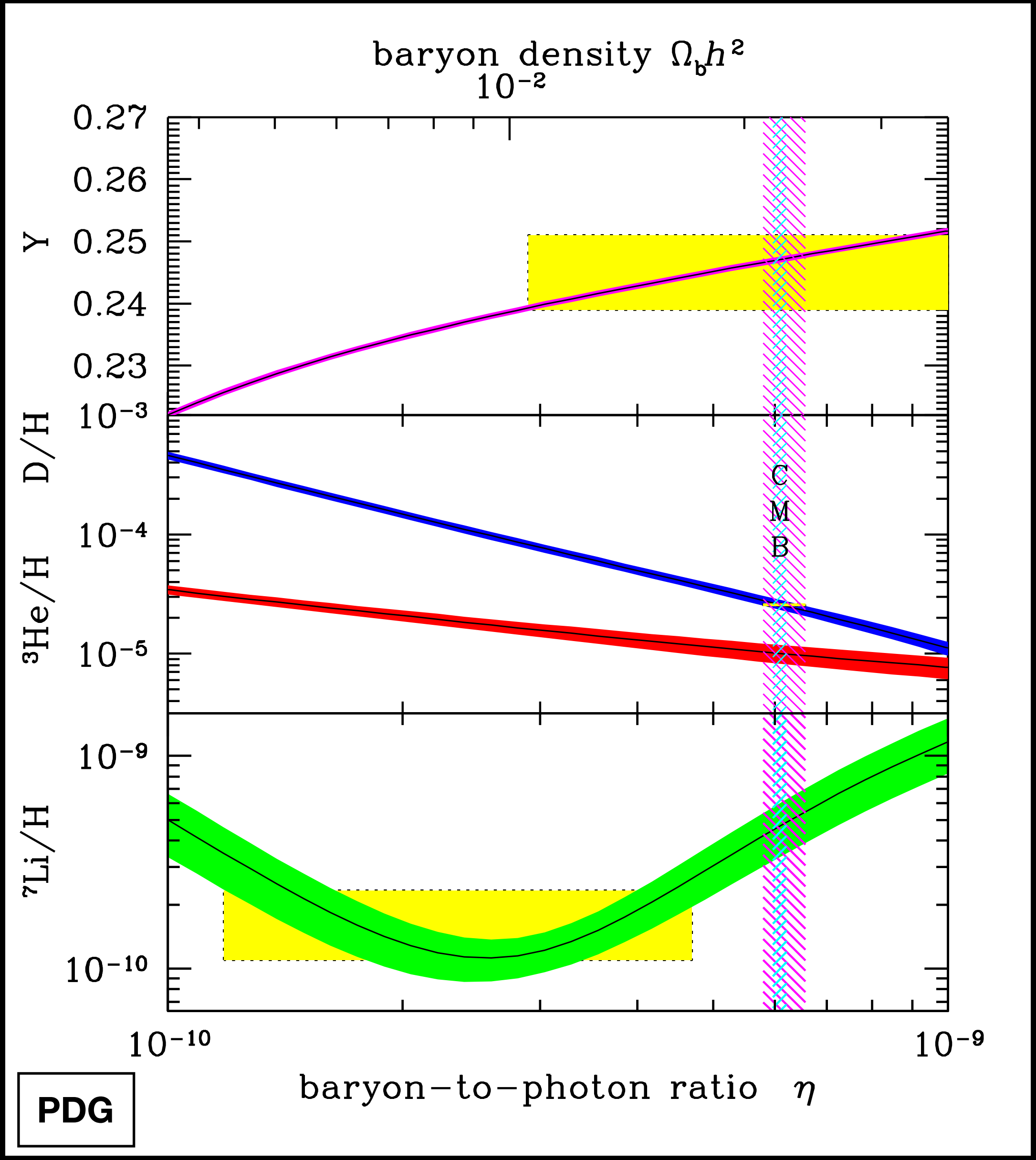


$69.99 for 20 servings

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

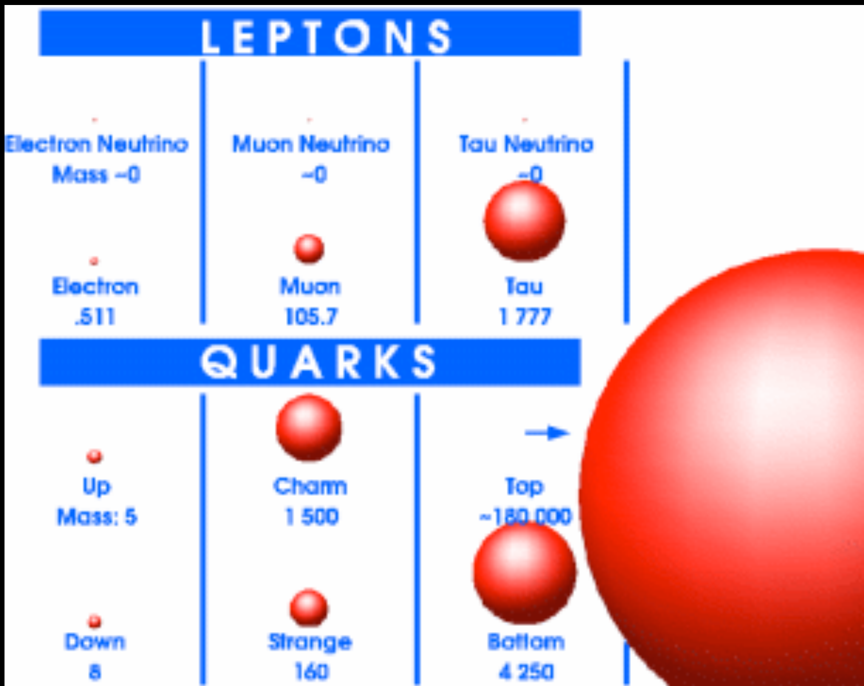
Generating a baryon asymmetry from a baryon symmetric starting point requires very particular physics:

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.

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?

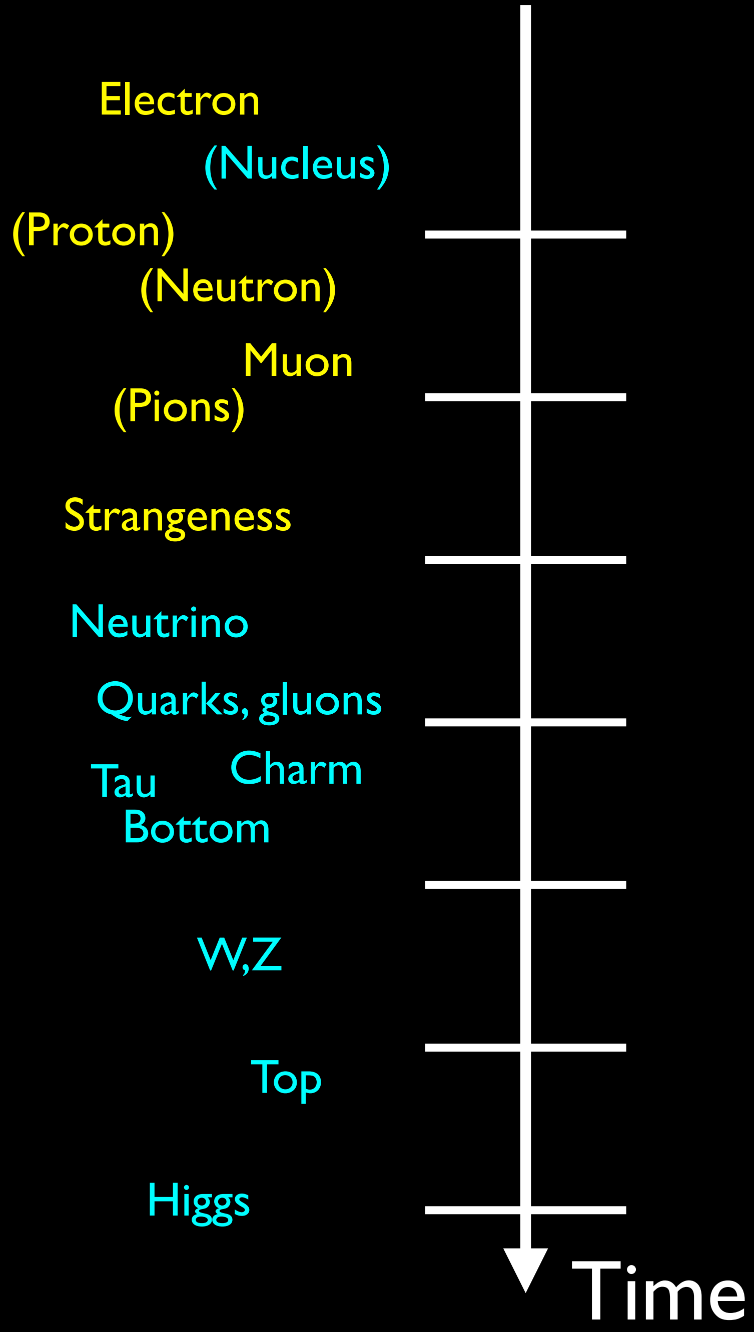


More Clouds than Sky?

Sydney, Nova Scotia

The Role of Accelerators

- It's fair to say that the bulk of our understanding of the Standard Model has been the result of analyzing data from accelerators.
- Accelerators offer a tightly controlled, usually well understood initial state.
- By converting energy into mass, accelerators will produce any new particles whose masses are kinematically accessible and with sufficiently large couplings.
  - Even if we don't know that they are there!
  - That makes them a good place to look for the unknown and unexpected.



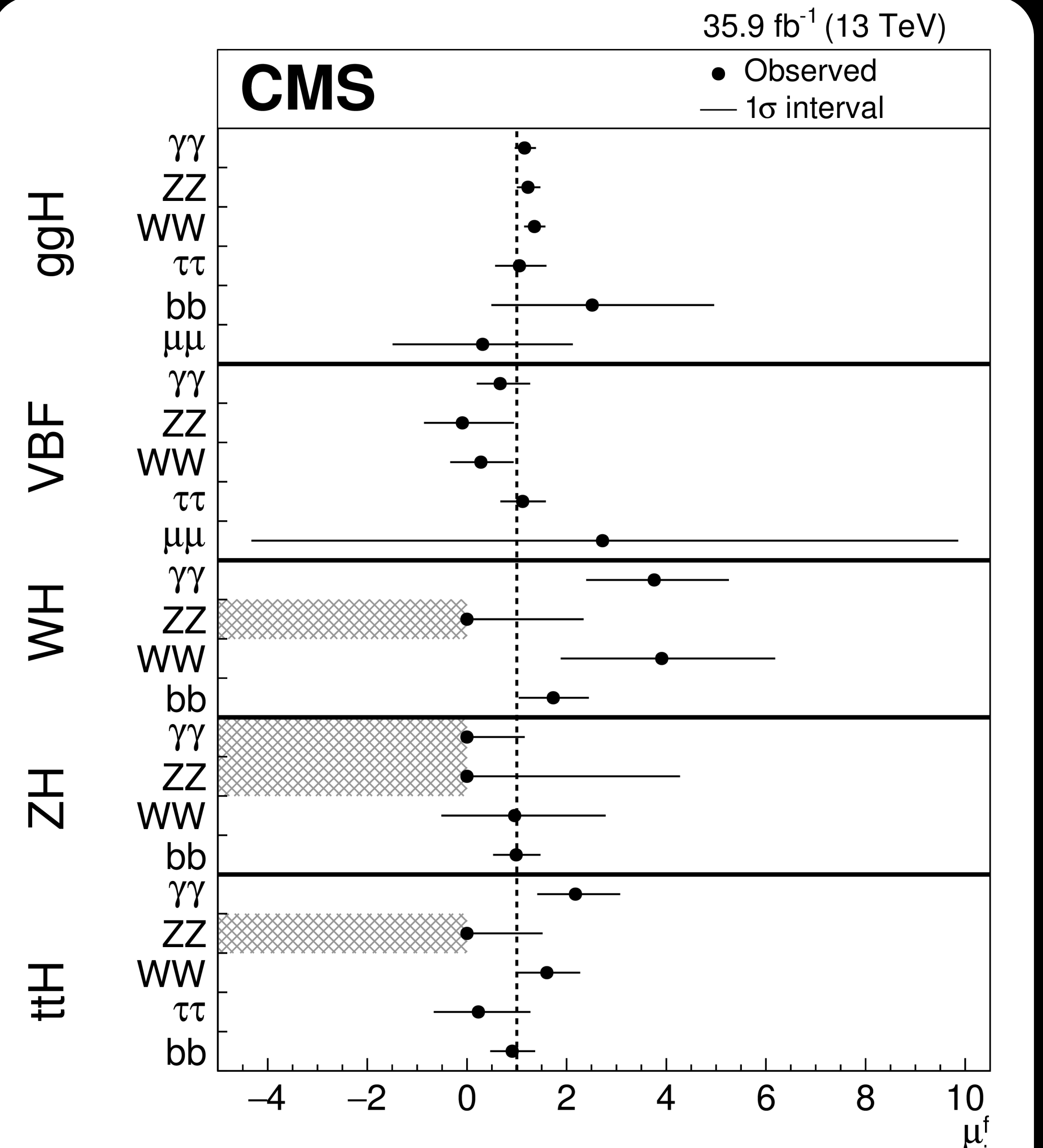
More Clouds than Sky?

Sydney, Nova Scotia

Higgs Properties

- An important contribution we can expect from future colliders is to precisely measure the properties of the Higgs.
- The LHC already has produced many Higgs bosons, and running with high luminosity it will produce many more in a variety of channels, and observe a large number of its decay modes.
- The LHC has measured many important quantities to ~10% or so.

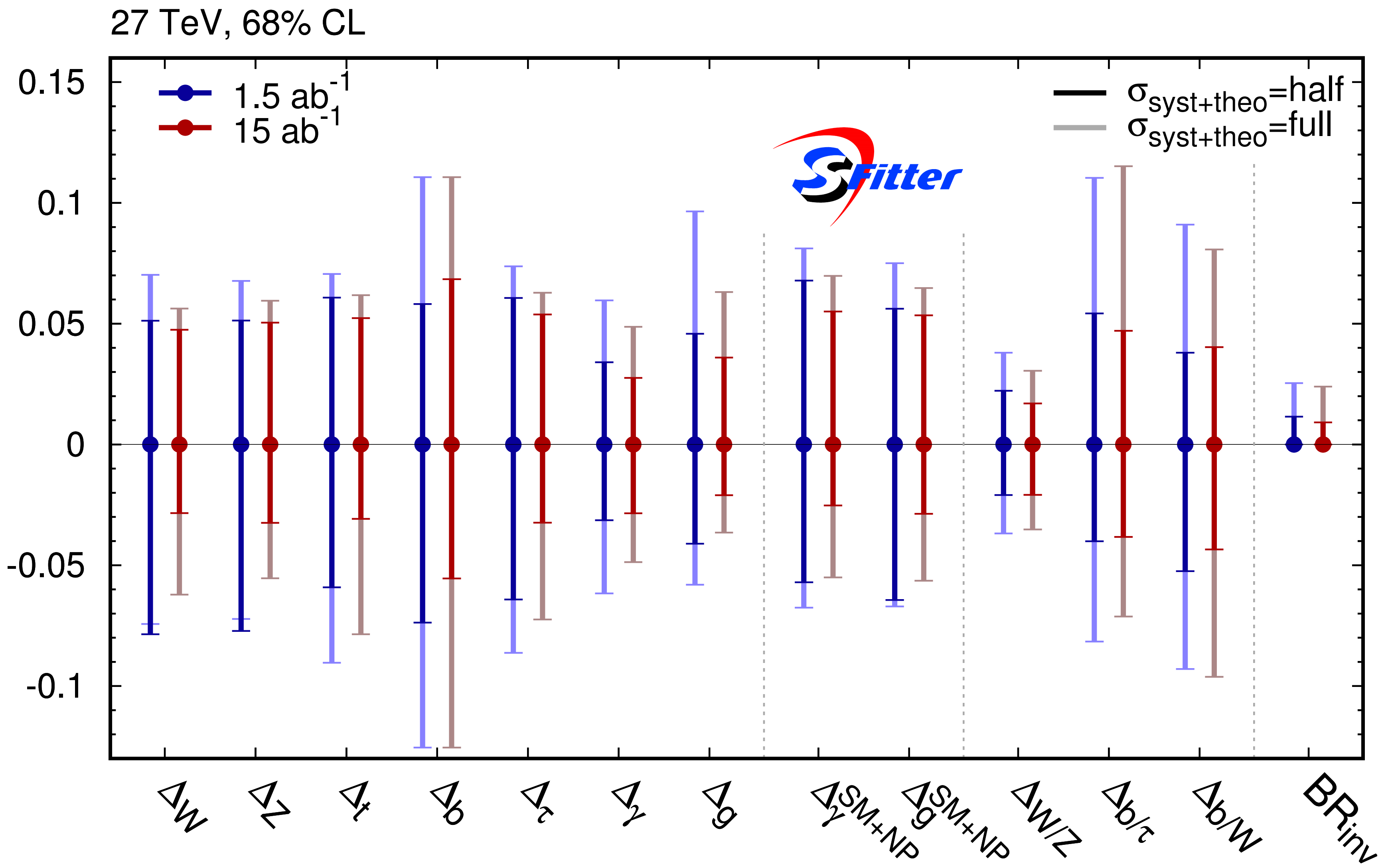
(See also the talk by Demers yesterday)



CMS-HIG-17-031

(Similar results from ATLAS)

Hadrons @ 27 TeV



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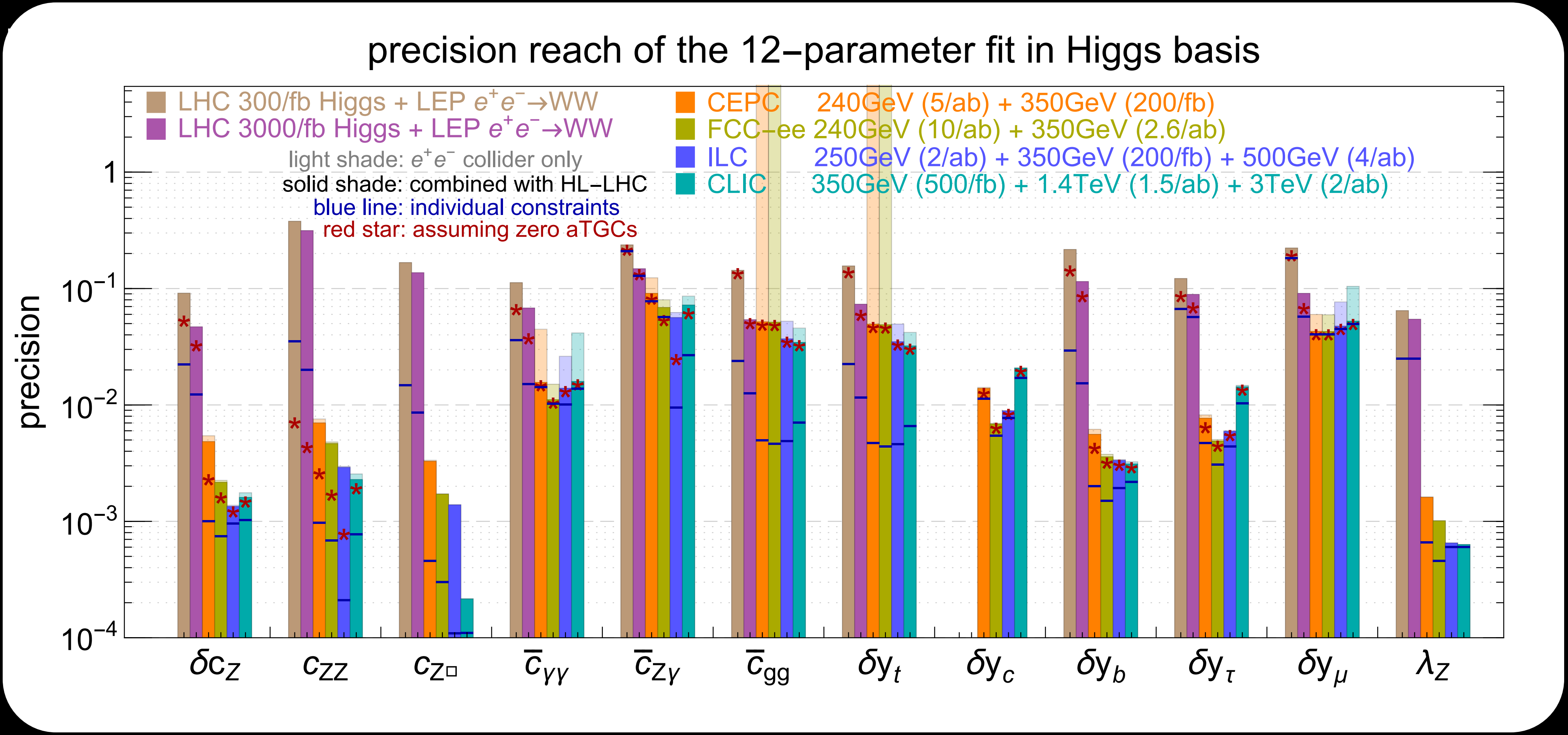
Lepton Colliders



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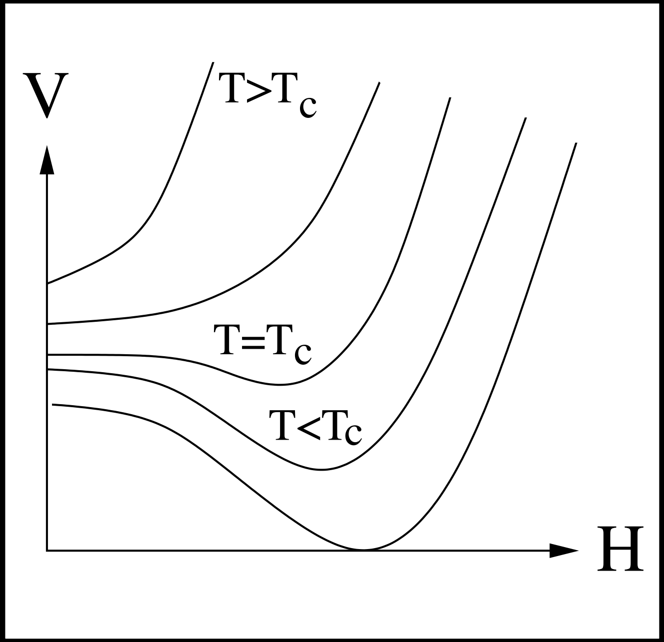
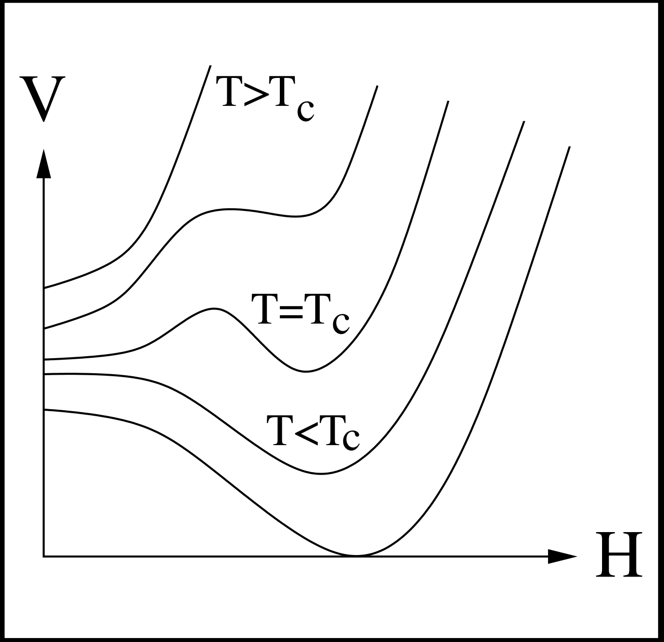
Higgs Self-Coupling

- 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.

Cross-over (SM prediction)



1st Order (needed for electroweak baryogenesis)



Higgs Self-Coupling

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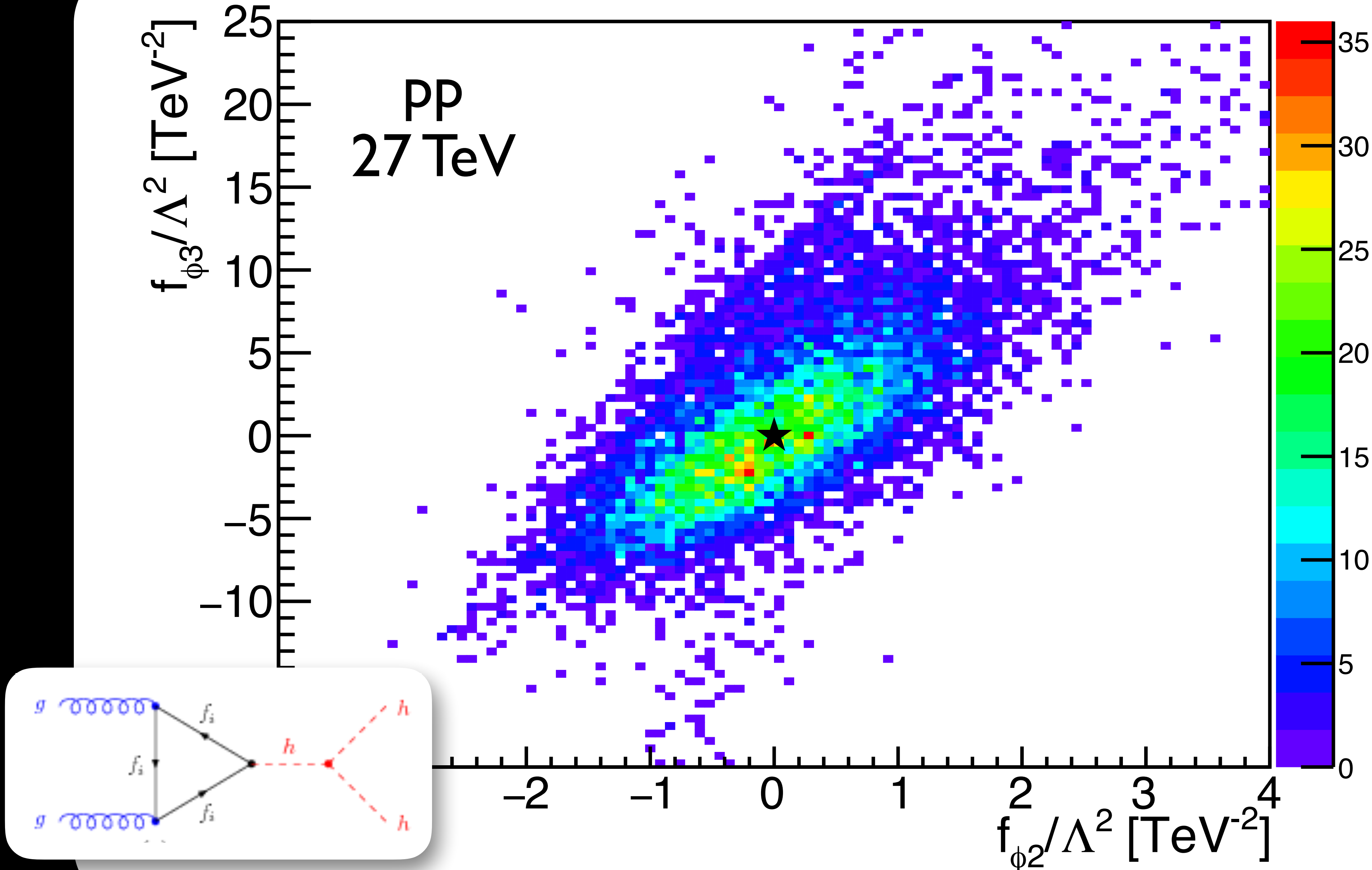
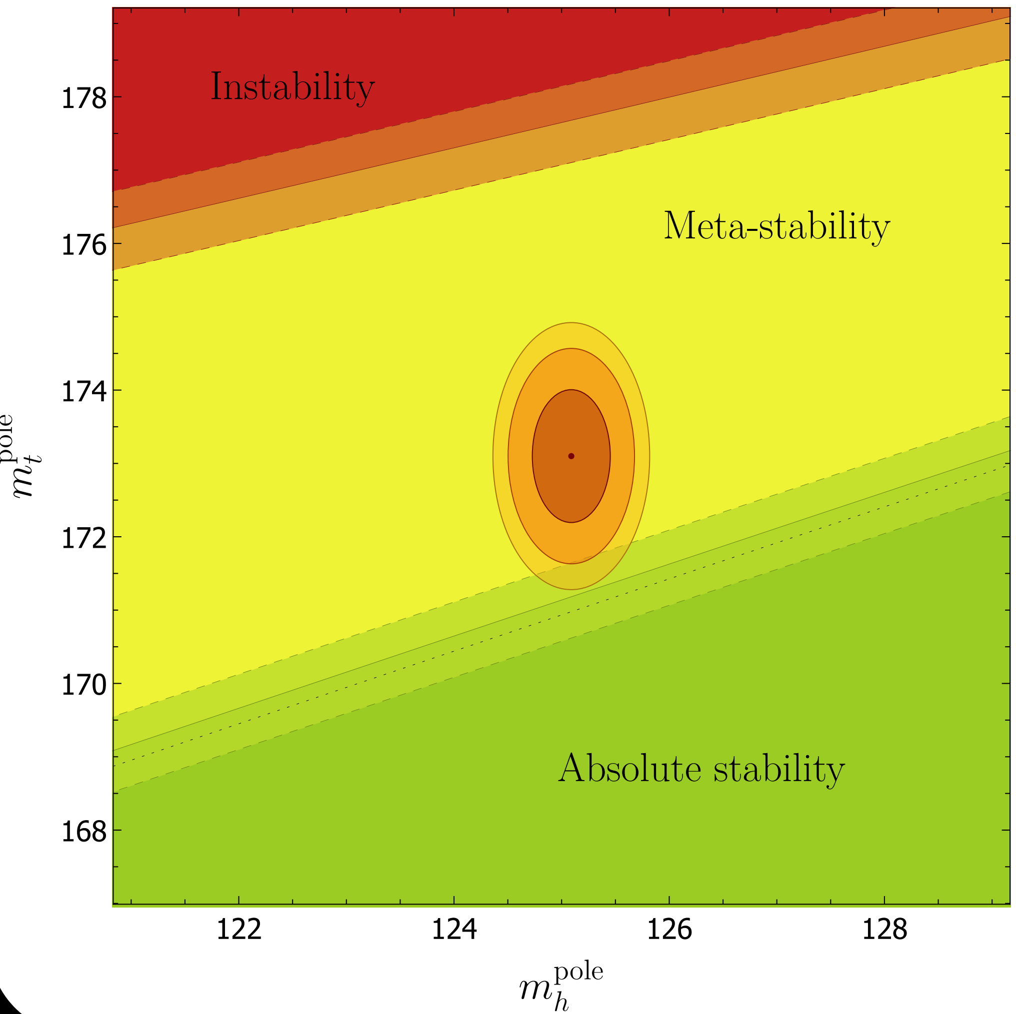
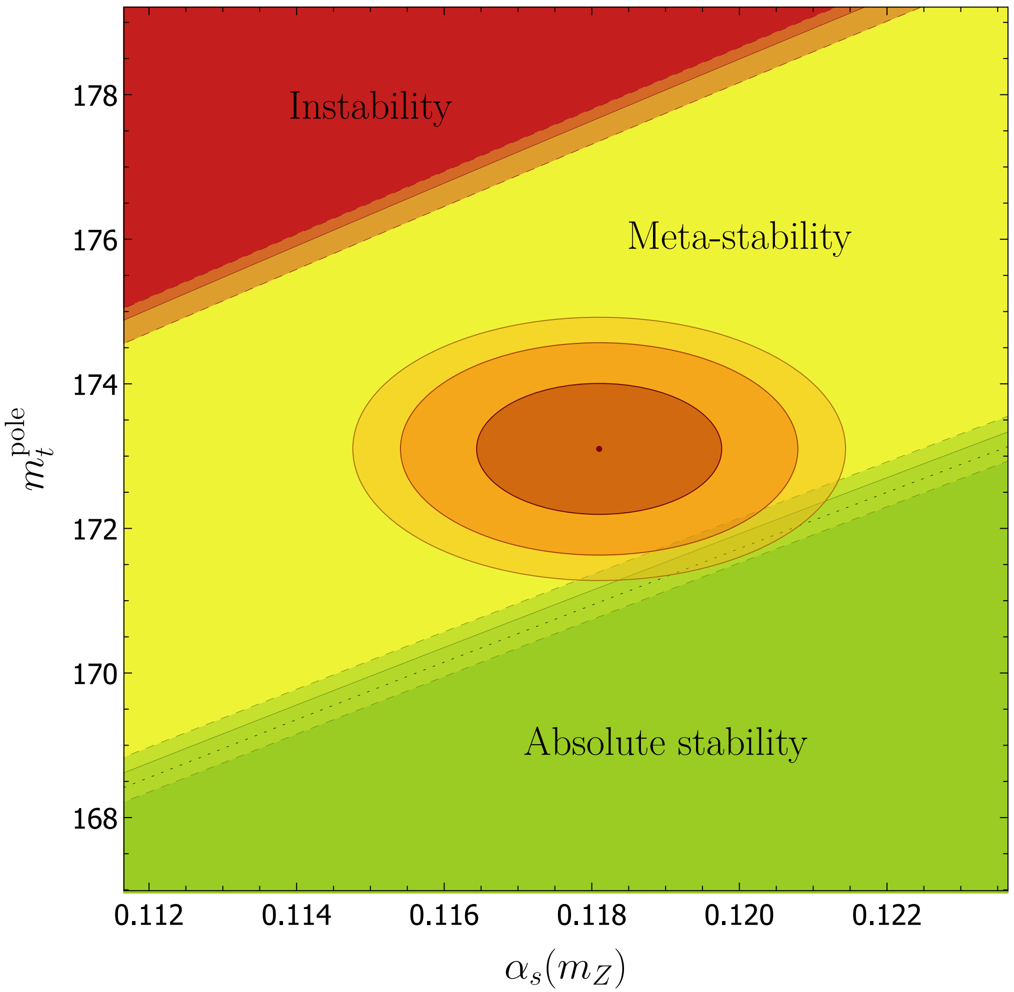


The Fate of the Universe





…rests on the measurement of the top mass…

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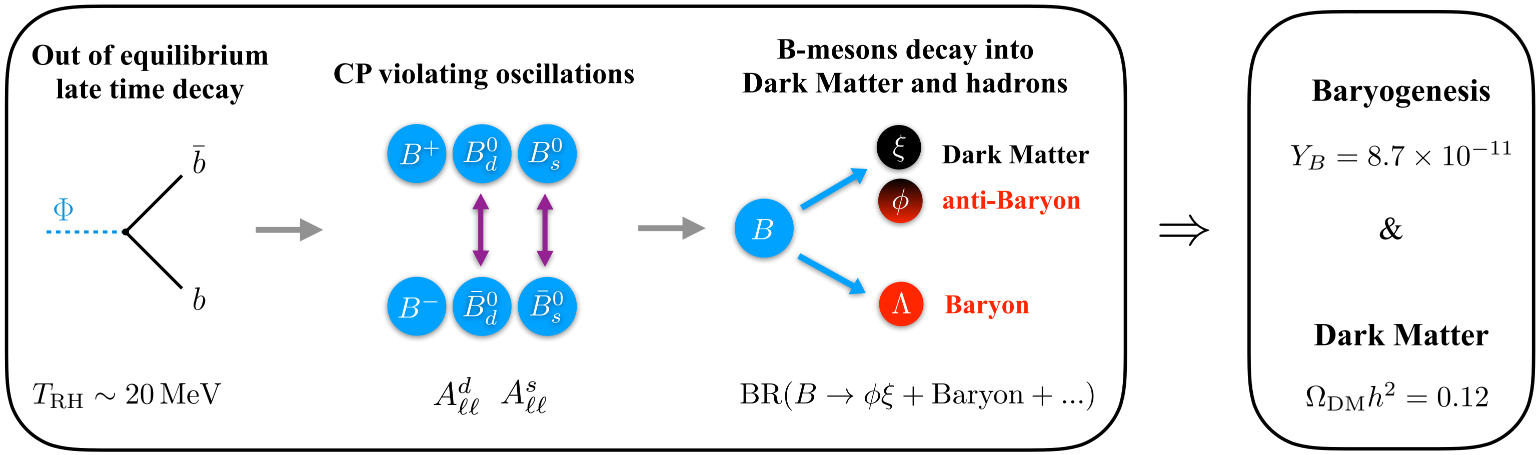
CP Violation in B Mesons



Elor, Escudero, Nelson
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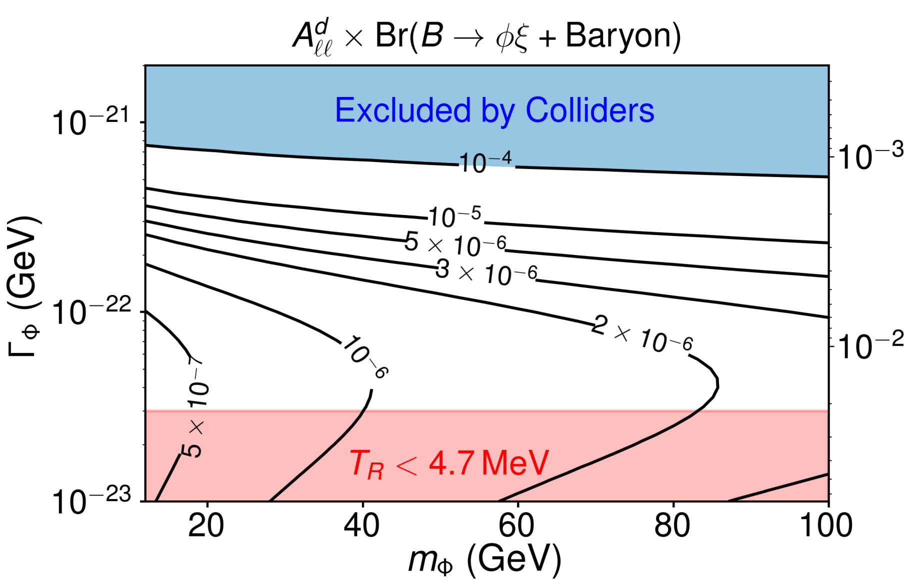
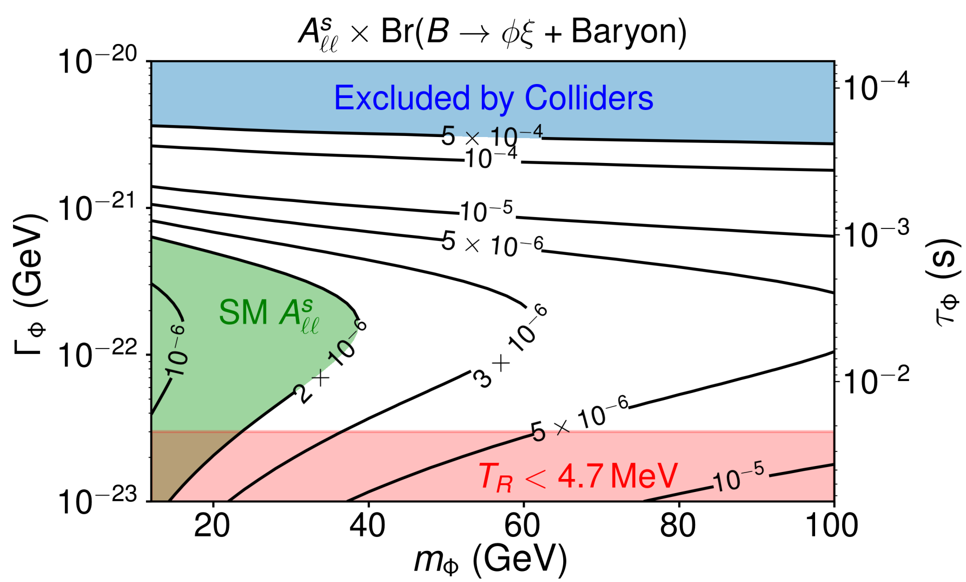
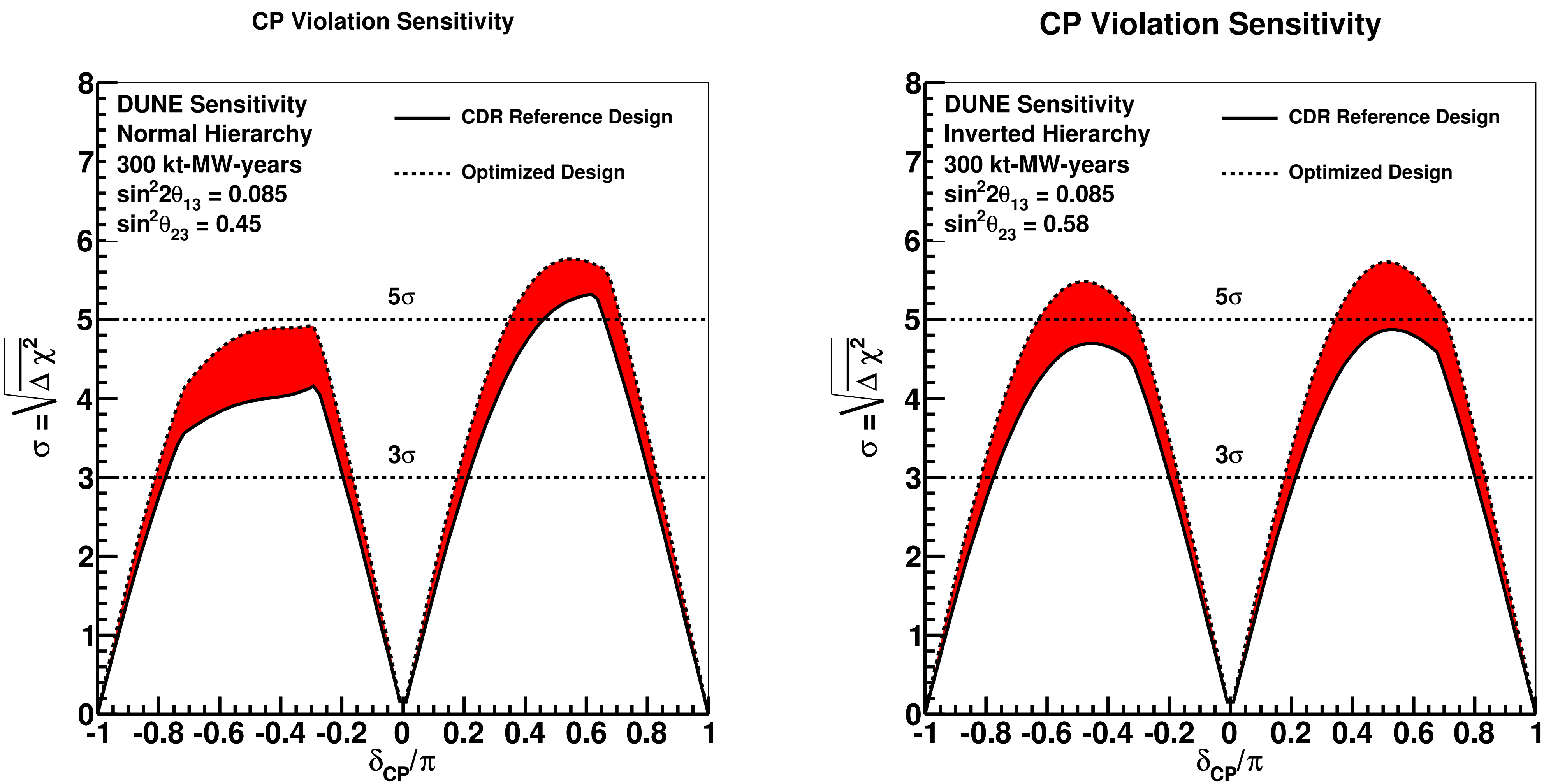
(See also: McKeen talk on Tuesday)





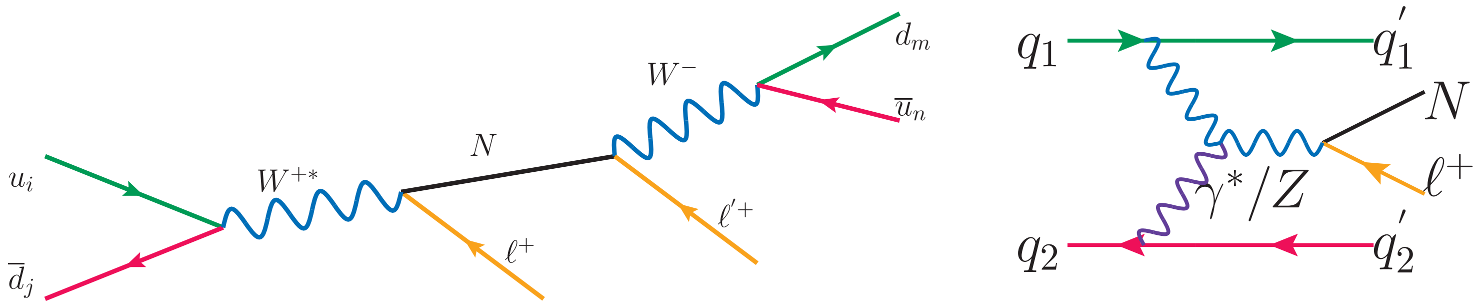
…could drive the baryon asymmetry of the Universe!

CP Violation from Neutrinos?

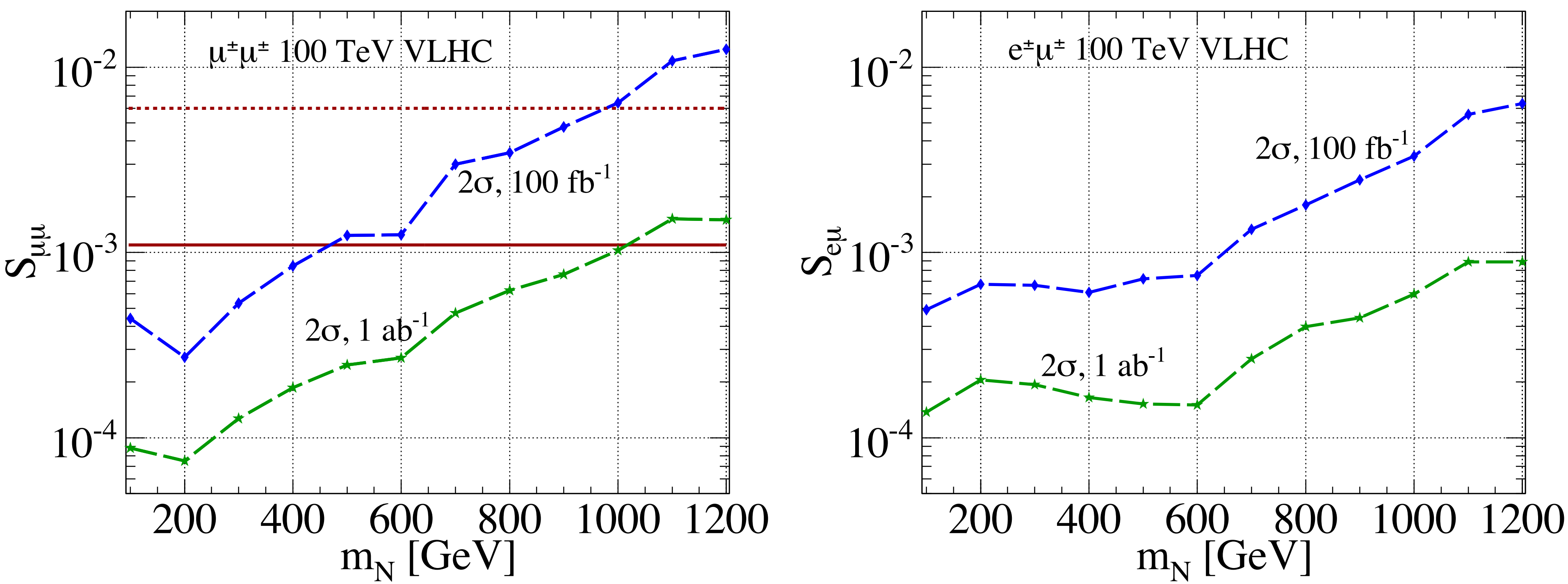


DUNE TDR

The Origin of Neutrino Masses



$$S_{\ell\ell'} = \frac{|V_{\ell N}|^2 |V_{\ell' N}|^2}{\sum_{\ell''} |V_{\ell'' N}|^2}$$



Future hadron colliders could produce the see-saw partners of the neutrinos.

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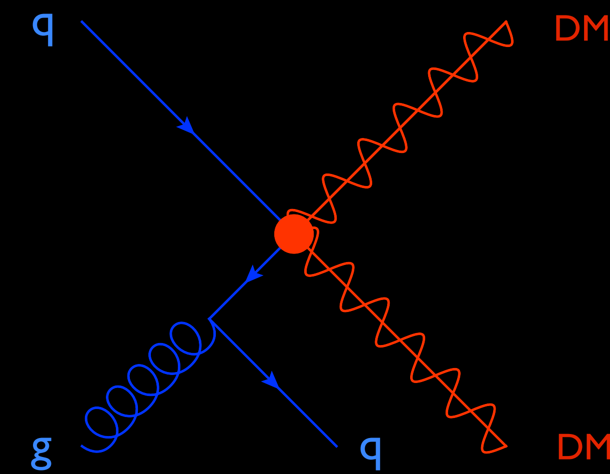
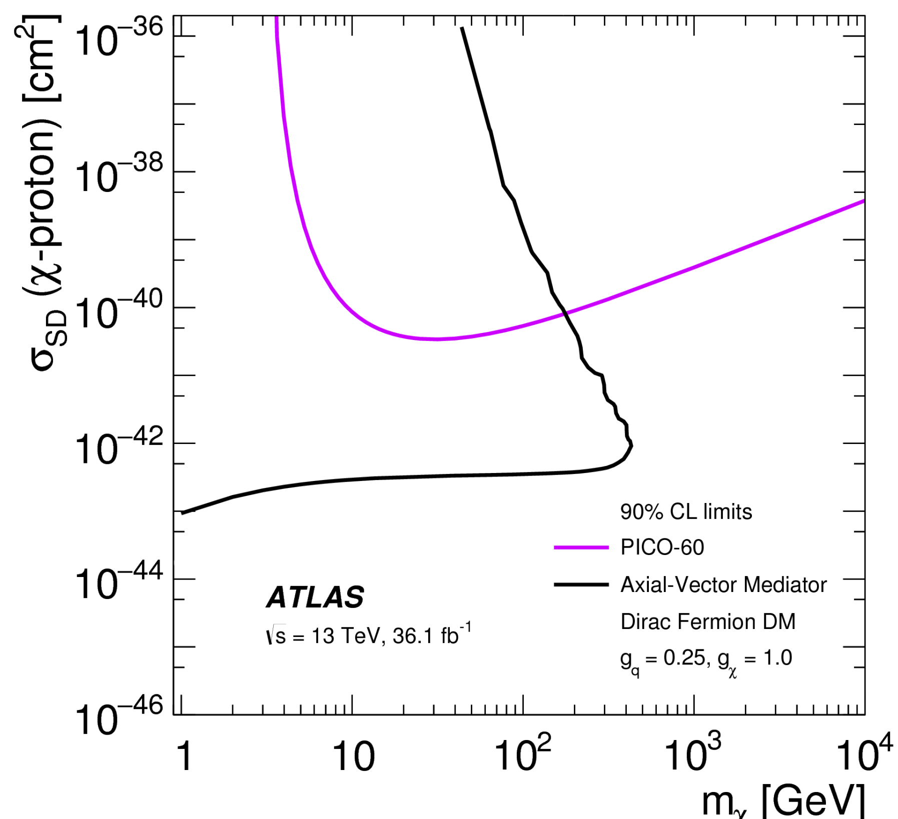
Dark Matter?



- 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.



(Similar results from CMS)

Dark Matter

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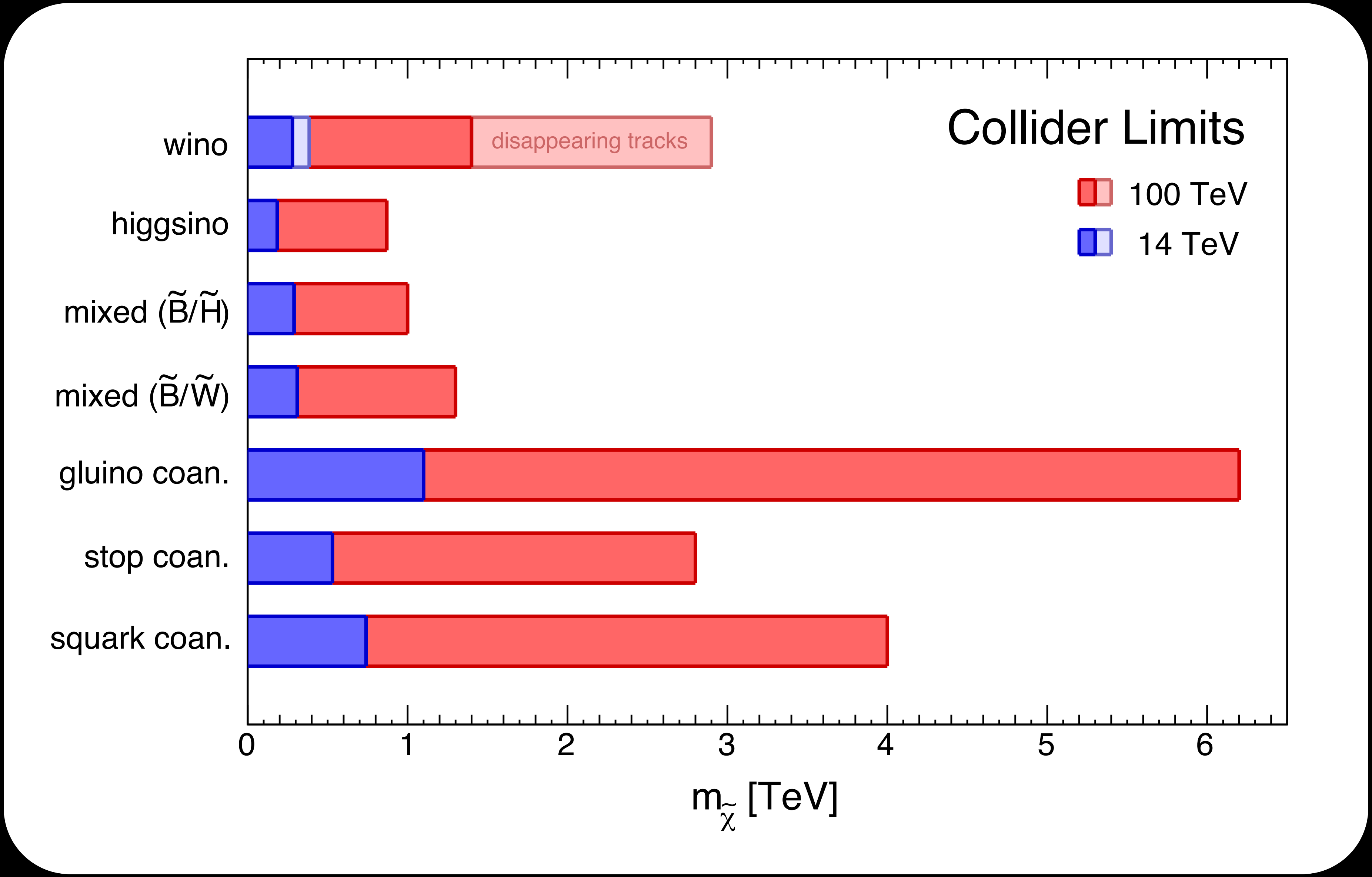
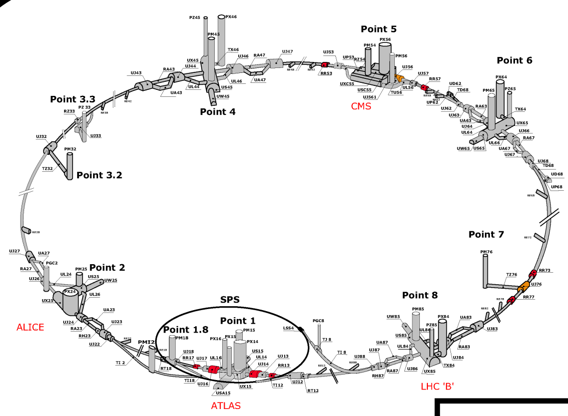
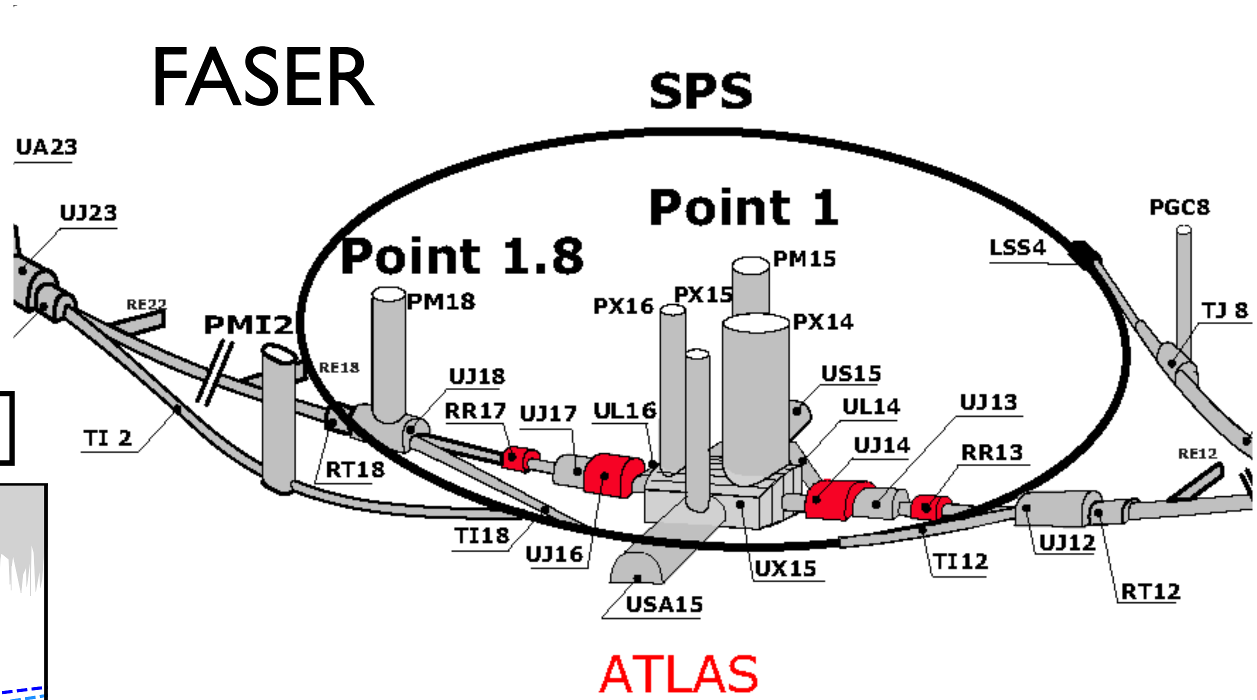
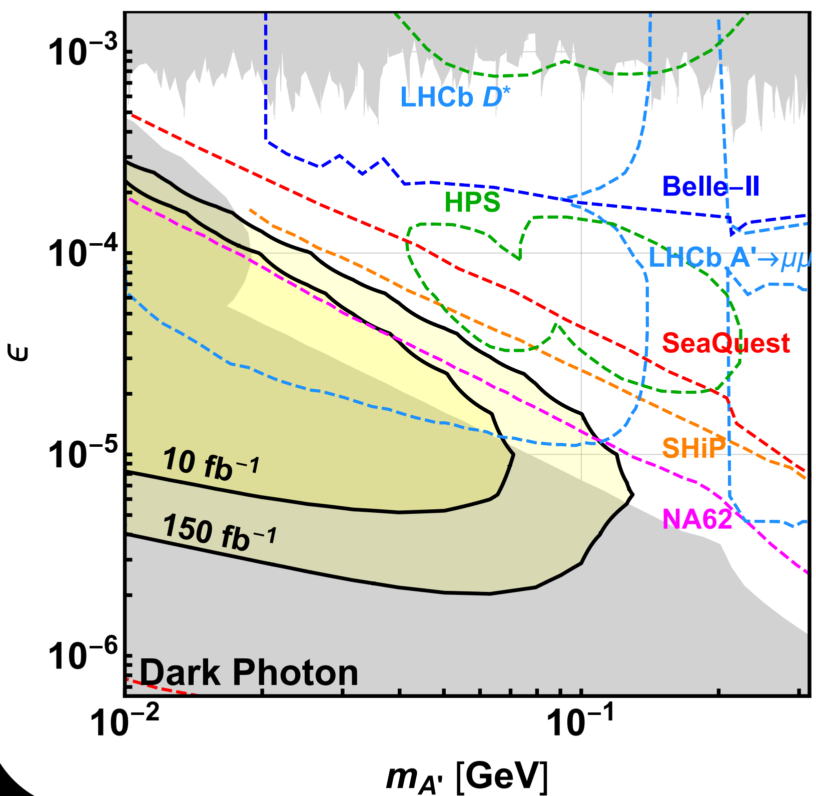


Access to the Dark Sector?



Courtesy of J Feng





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

(See also: Shuve talk on Tuesday)

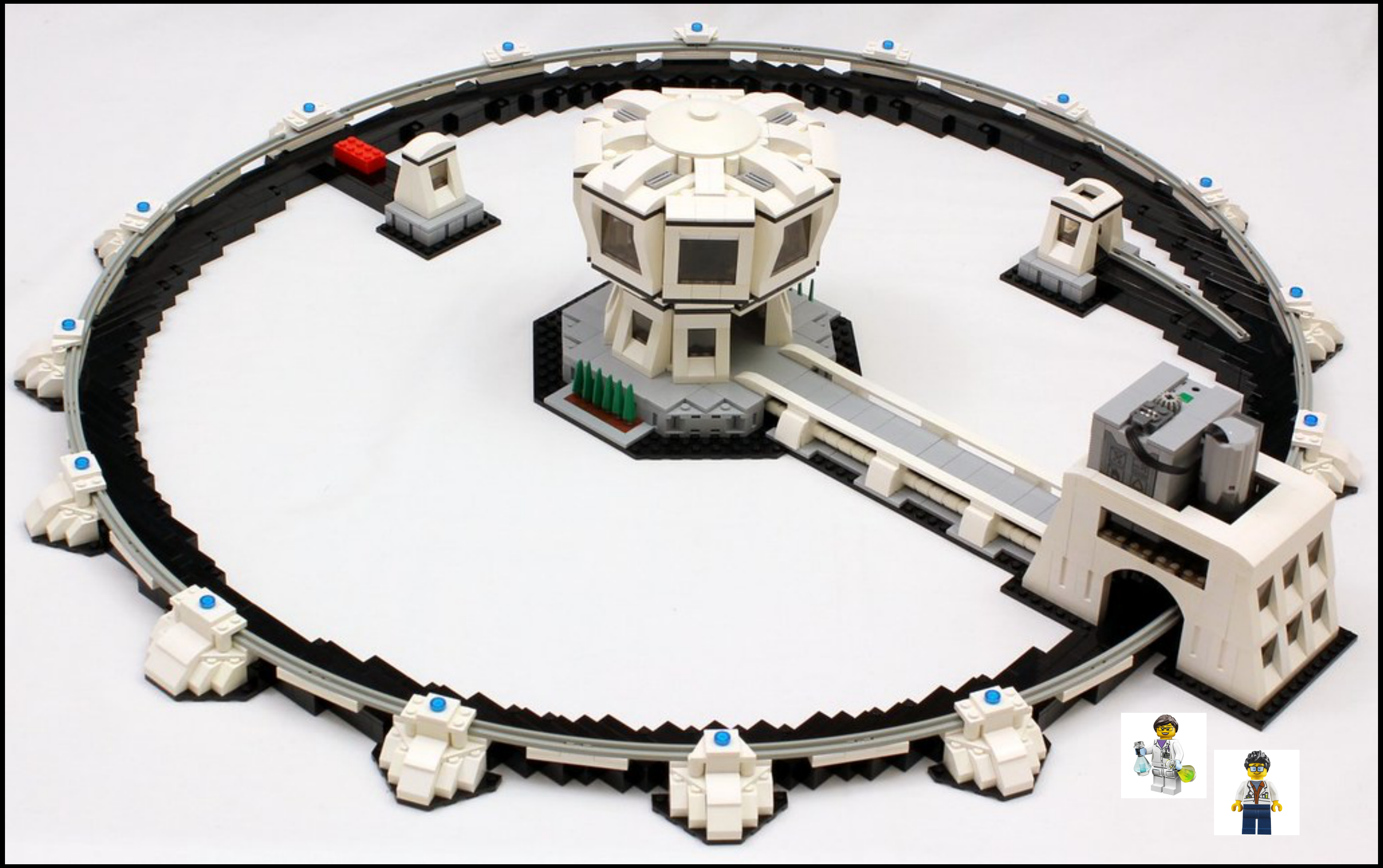
The Future Gets Brighter?

Cagliari, Sardegna

Outlook

- The Standard Model is a triumph, but it is incomplete:
  - Dark matter and dark energy
  - Baryon asymmetry
  - Neutrino masses
  - …and I didn’t even mention any of the more theoretically motivated arguments for physics beyond the Standard Model…
- While all point to physics beyond the Standard Model, none have an identified energy scale associated with their dynamics.
  - There isn’t a “no lose” theorem for a certain energy, like we had for electroweak symmetry breaking.
- Nonetheless, accelerators **shine** as a tool to explore. The control over the initial state and the ability to produce the unexpected offer opportunities which are difficult to realize in any other way.

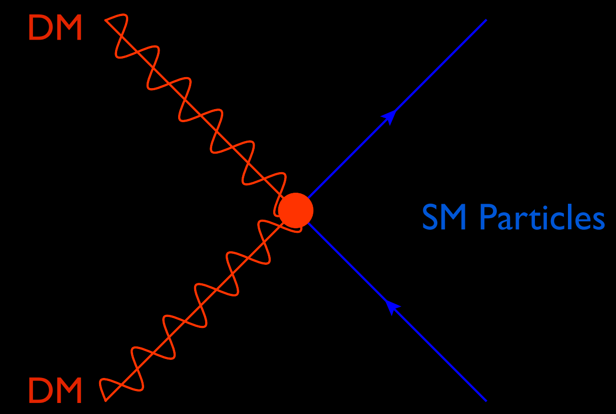
Outlook

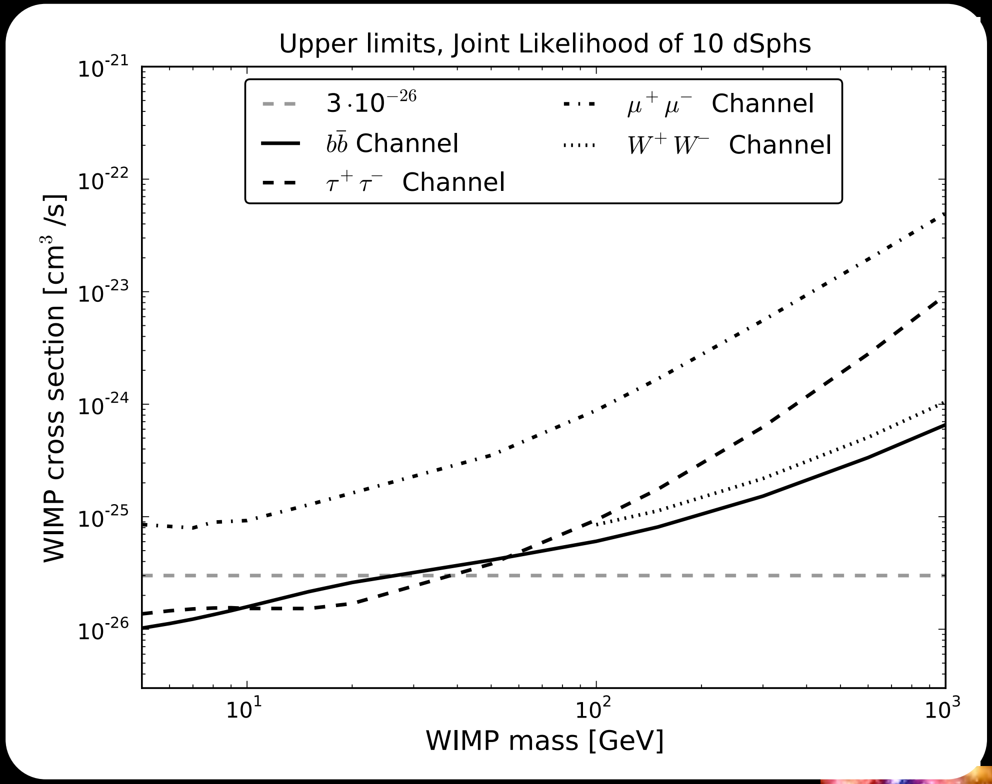


The only way to know is to build it!

Searching for Dark Matter

- Our observations of dark matter are through its gravitational effects. Does it have any other kind of interaction with ordinary matter?
- We have good reason to think it might have much stronger coupling than gravitational.
- If the dark matter has strong enough interactions, it will naturally be produced at early times when the Universe is dense and hot, and then freeze out to its current density.
- In this picture, the abundance of dark matter is controlled by the rate that it annihilates into ordinary matter. Can we observe such annihilation today?





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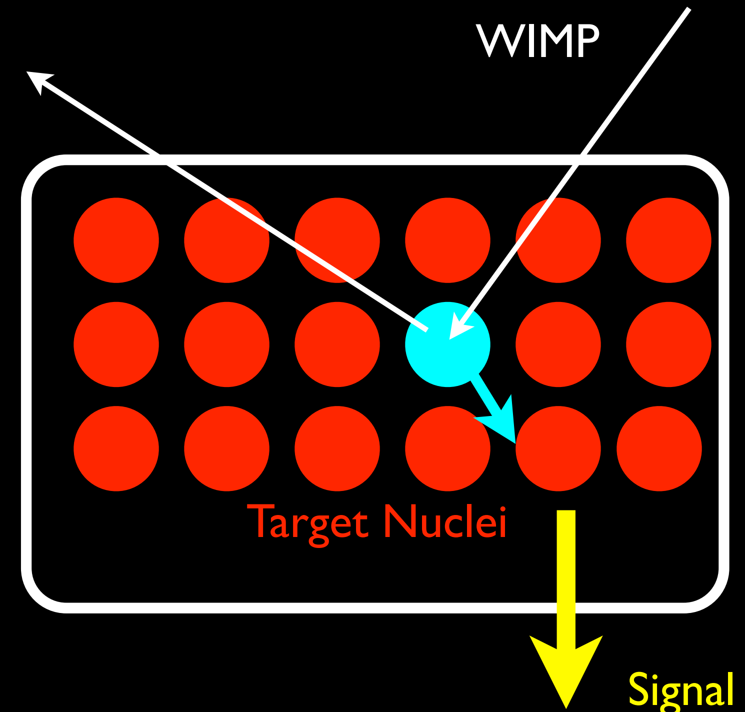
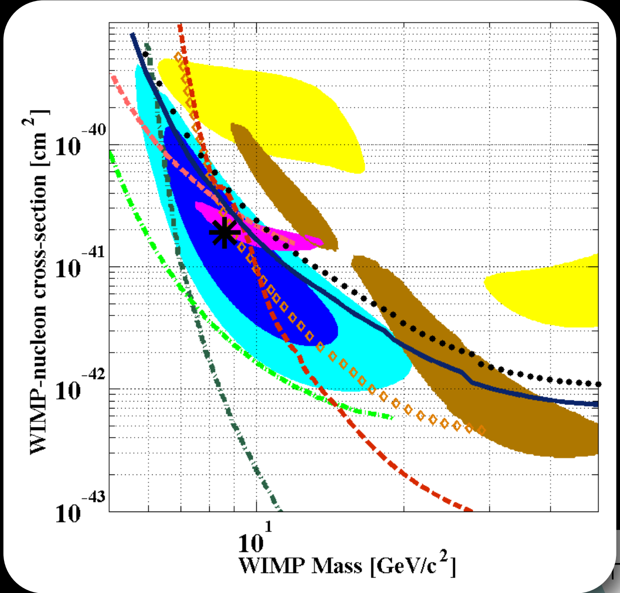
Searching for Dark Matter

- 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.





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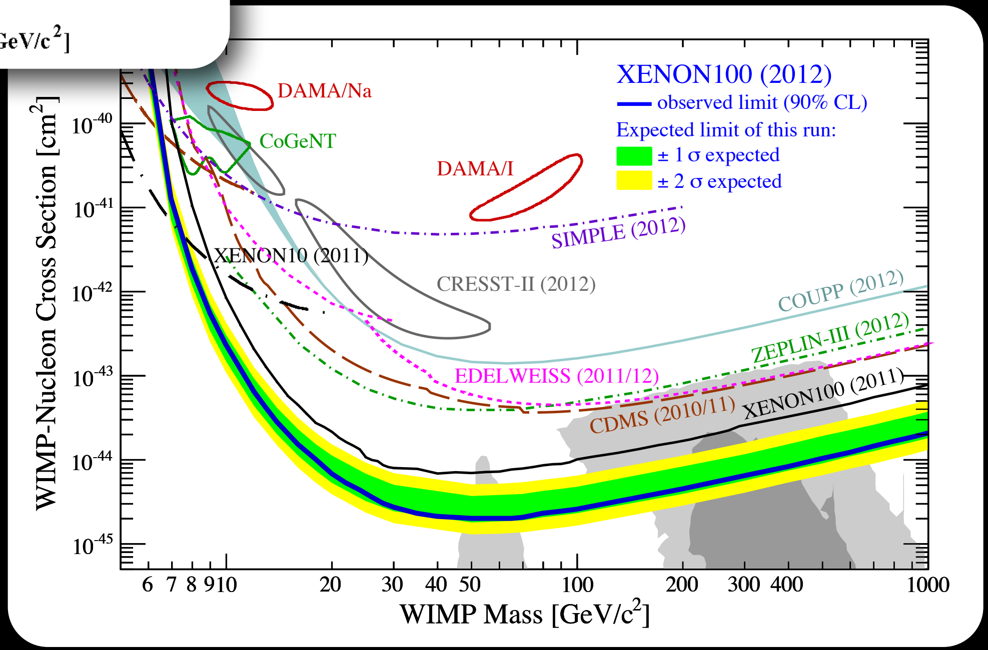

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