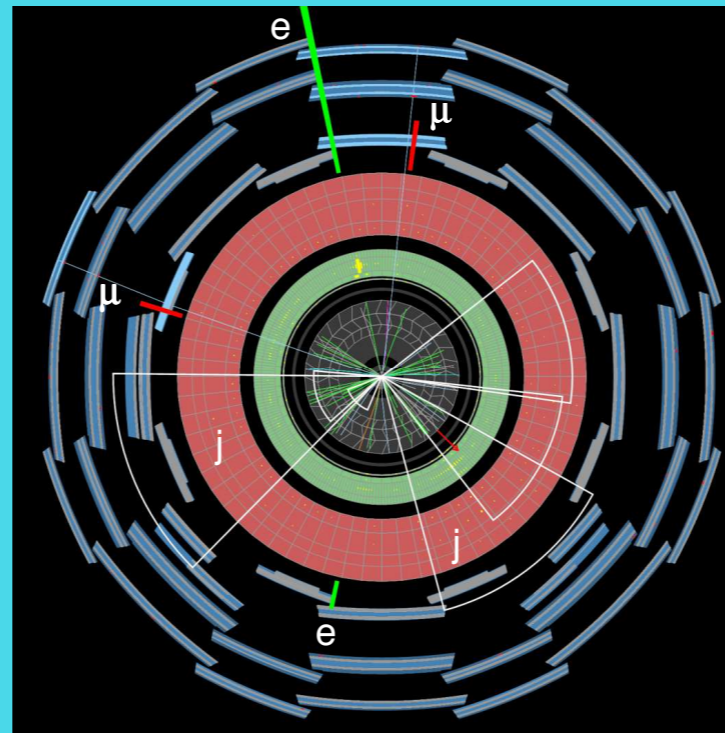


The Higgs boson is found: What is next?



Dmitry Kazakov

Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research (Dubna)

Moscow Institute of Physics and Technology



17 March 2016

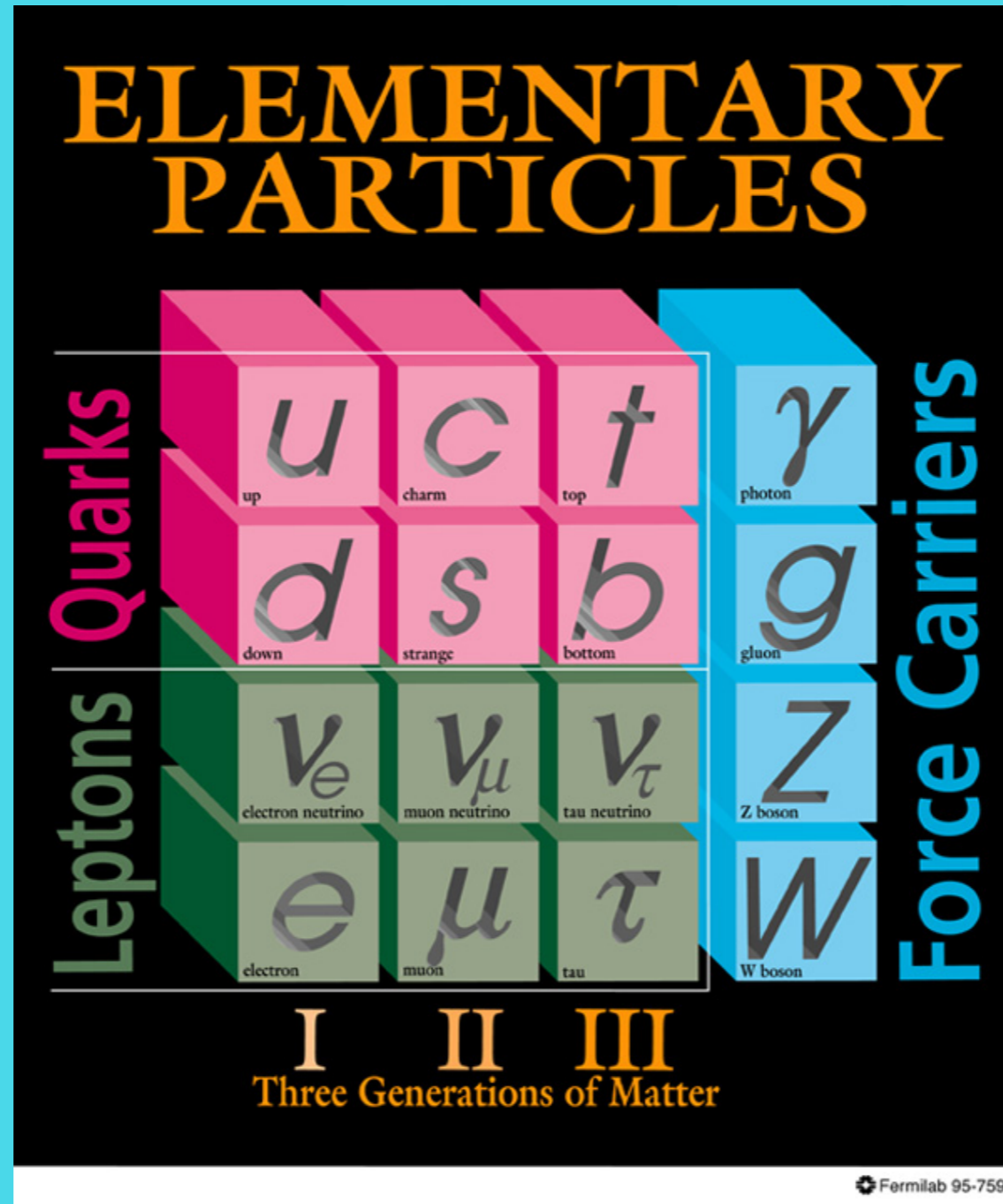
The Standard Model

SU(3)

SU(2)

U(1)

Standard Model



The Higgs boson

Gravity

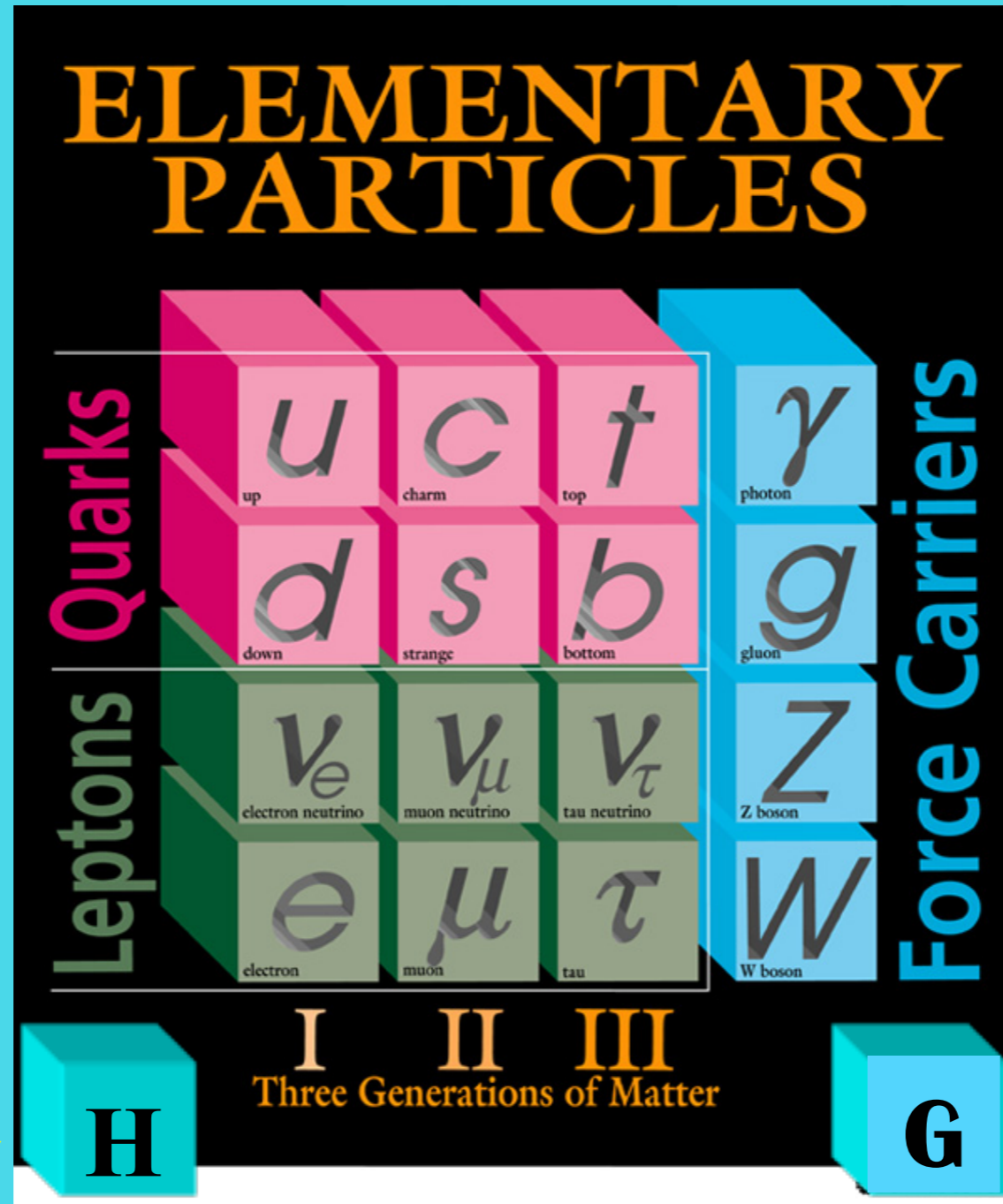
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Is it the end of a story or a step forward?

- This is the beginning of a new research program with decades to go.

The Standard Model of Fundamental Interactions

Higgs Sector

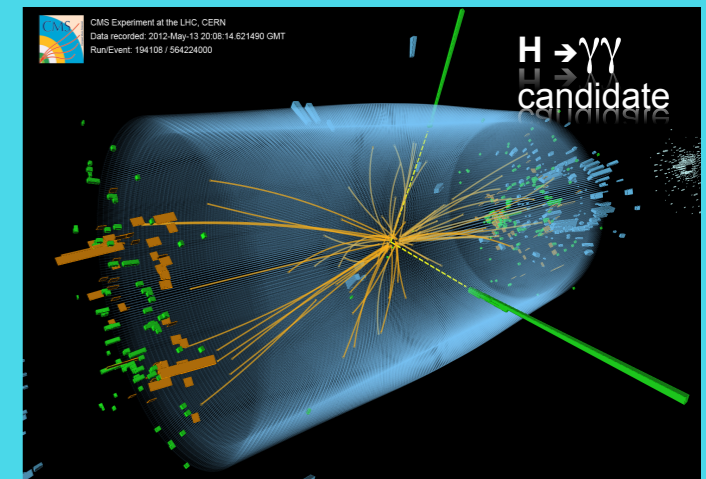
Neutrino Sector

Flavour Sector

Dark Matter

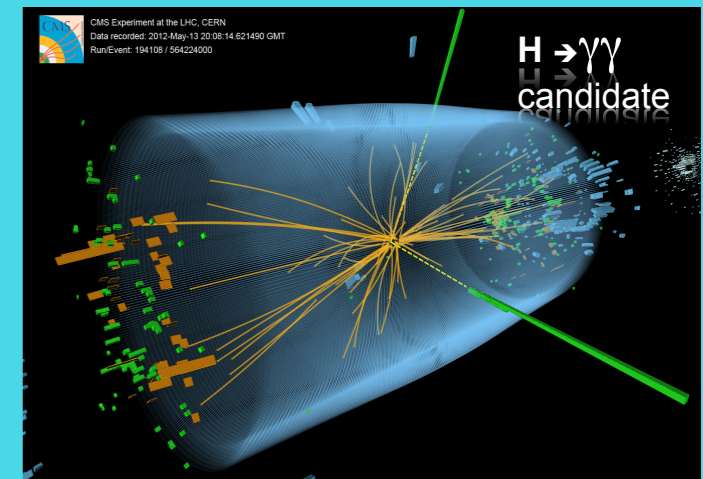
New particles and Interactions

The Higgs Sector



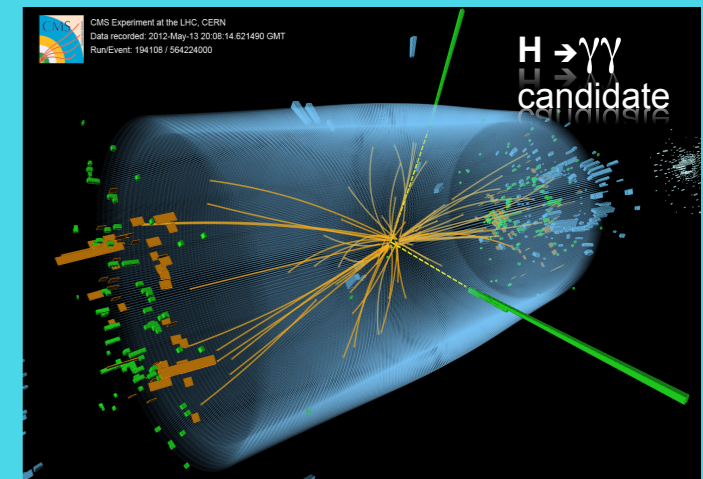
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- Is it the Higgs boson? - Almost sure



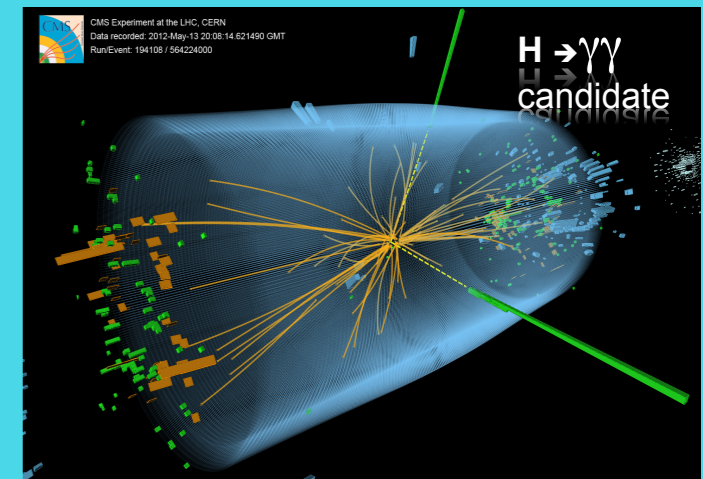
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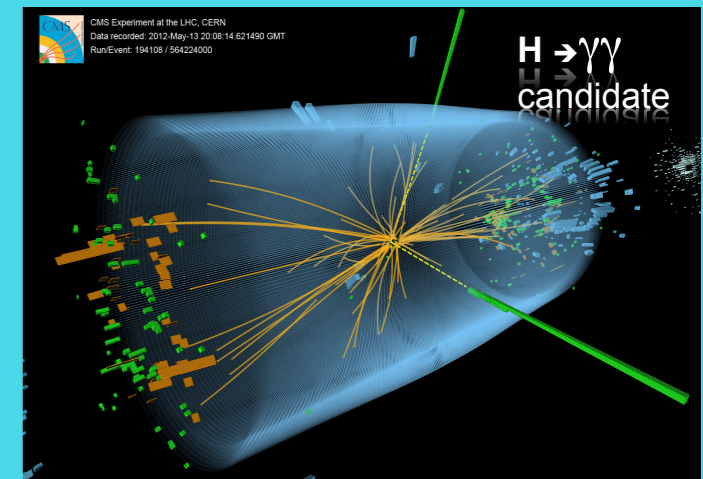
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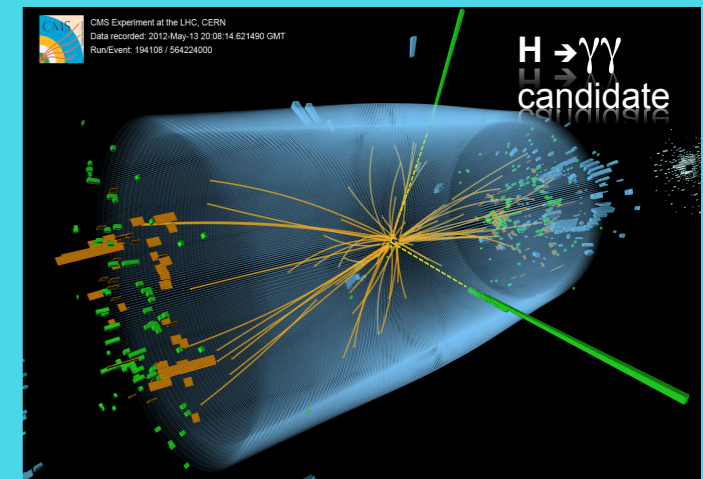
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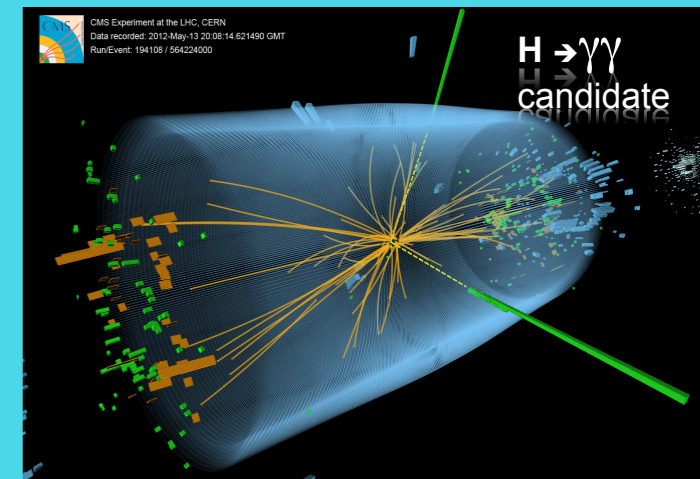
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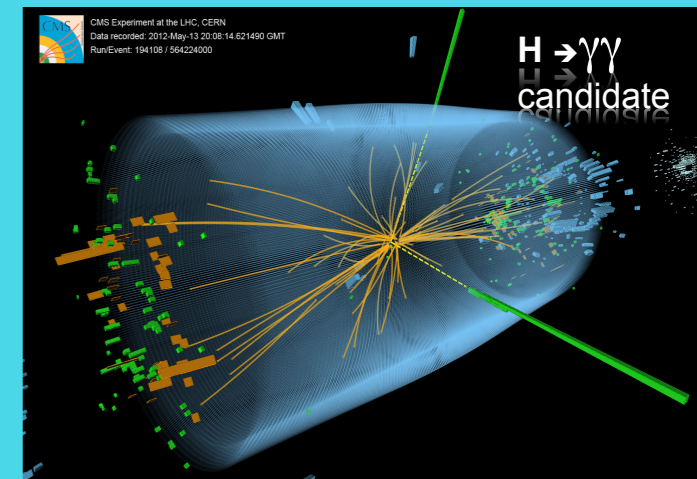
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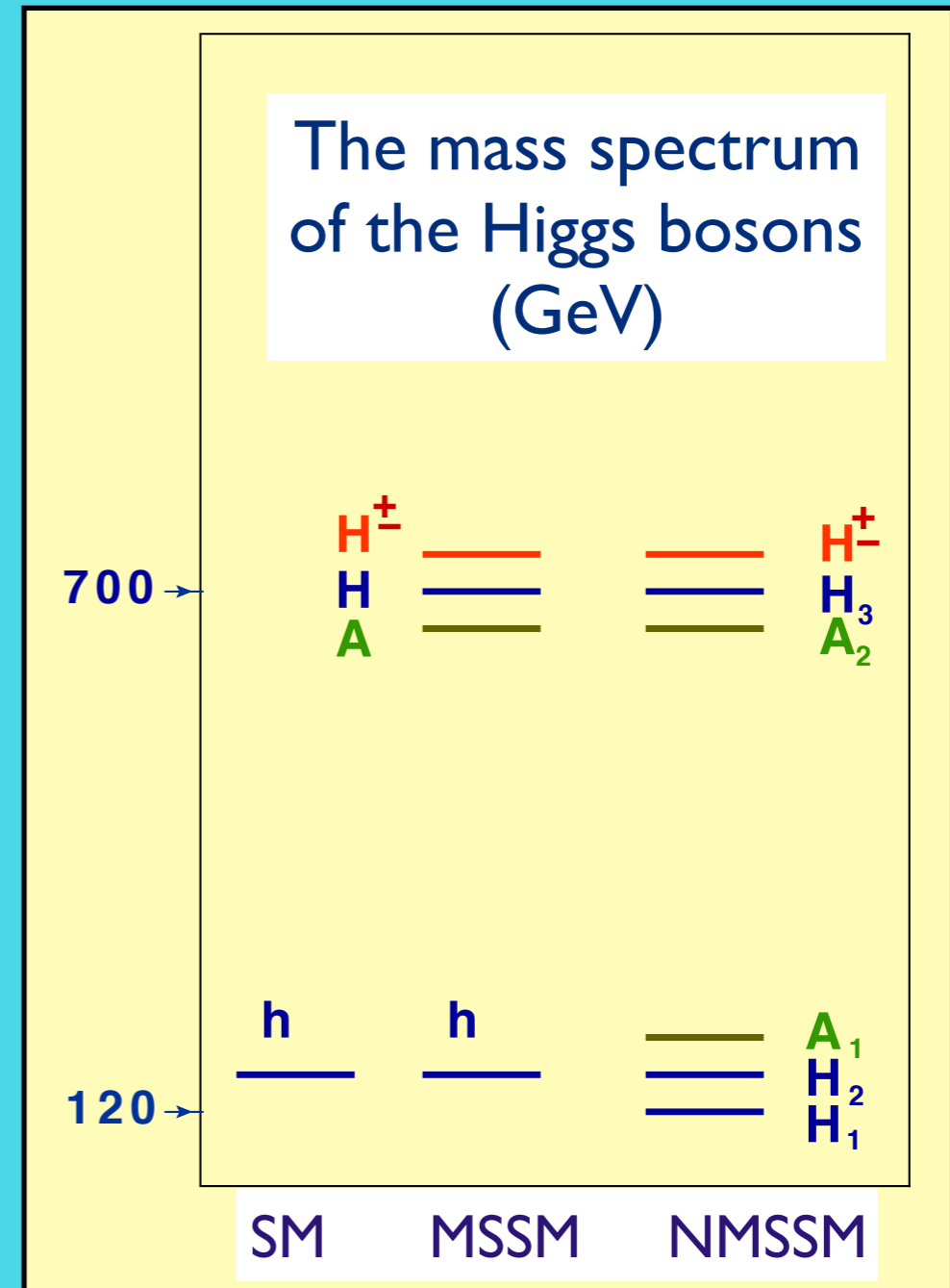
We have got the confirmation that particles obtain their masses as a result of interaction with the Brout-Englert-Higgs field (whatever model the Higgs boson belongs to)

The Higgs Sector: Alternatives

Model	Particle content
SM	h CP-even
2HDM/MSSM	h, H CP-even A CP-odd H^\pm
NMSSM	H_1, H_2, H_3 CP-even A_1, A_2 CP-odd H^\pm
Composite	h CP-even + excited states

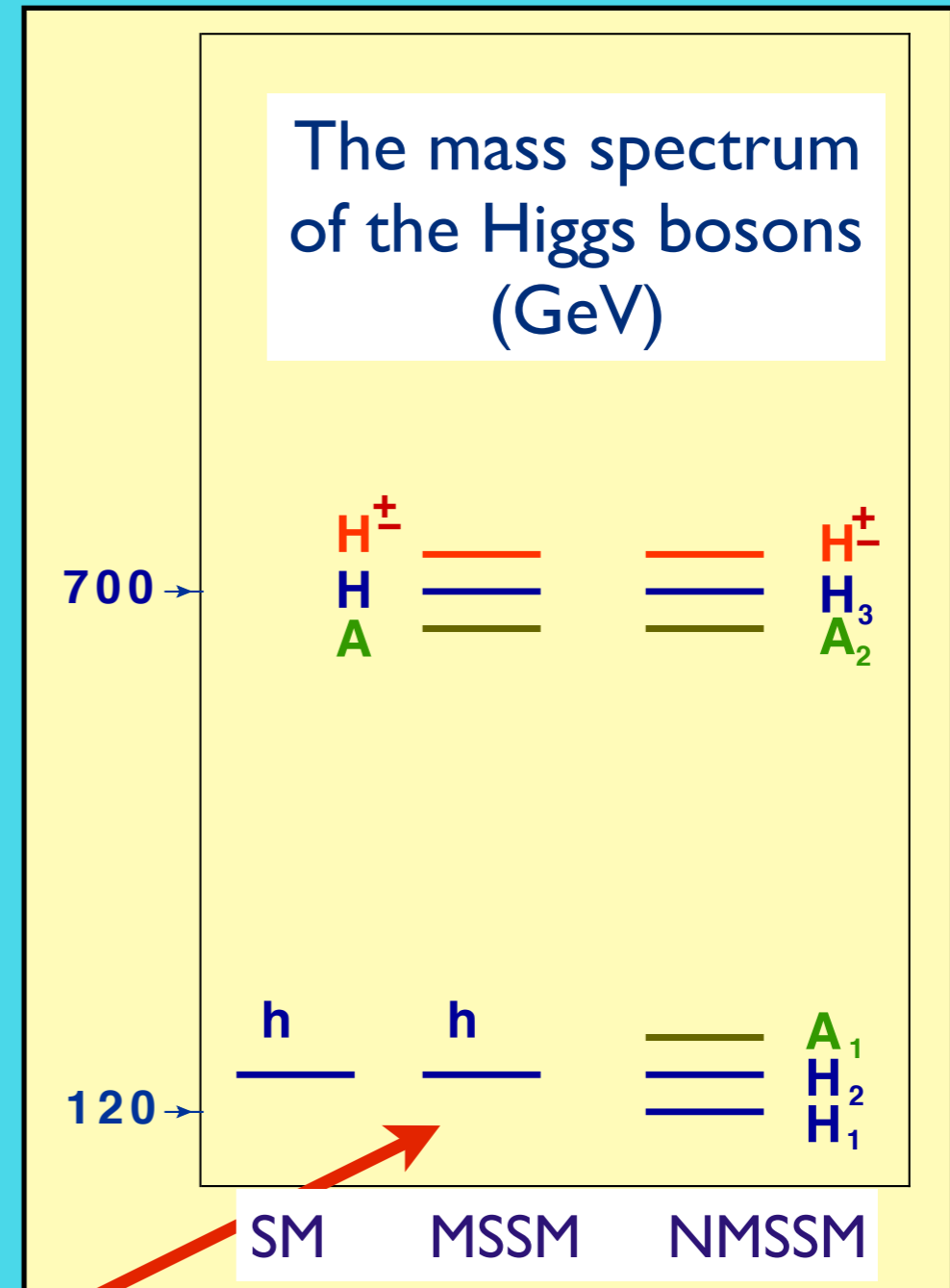
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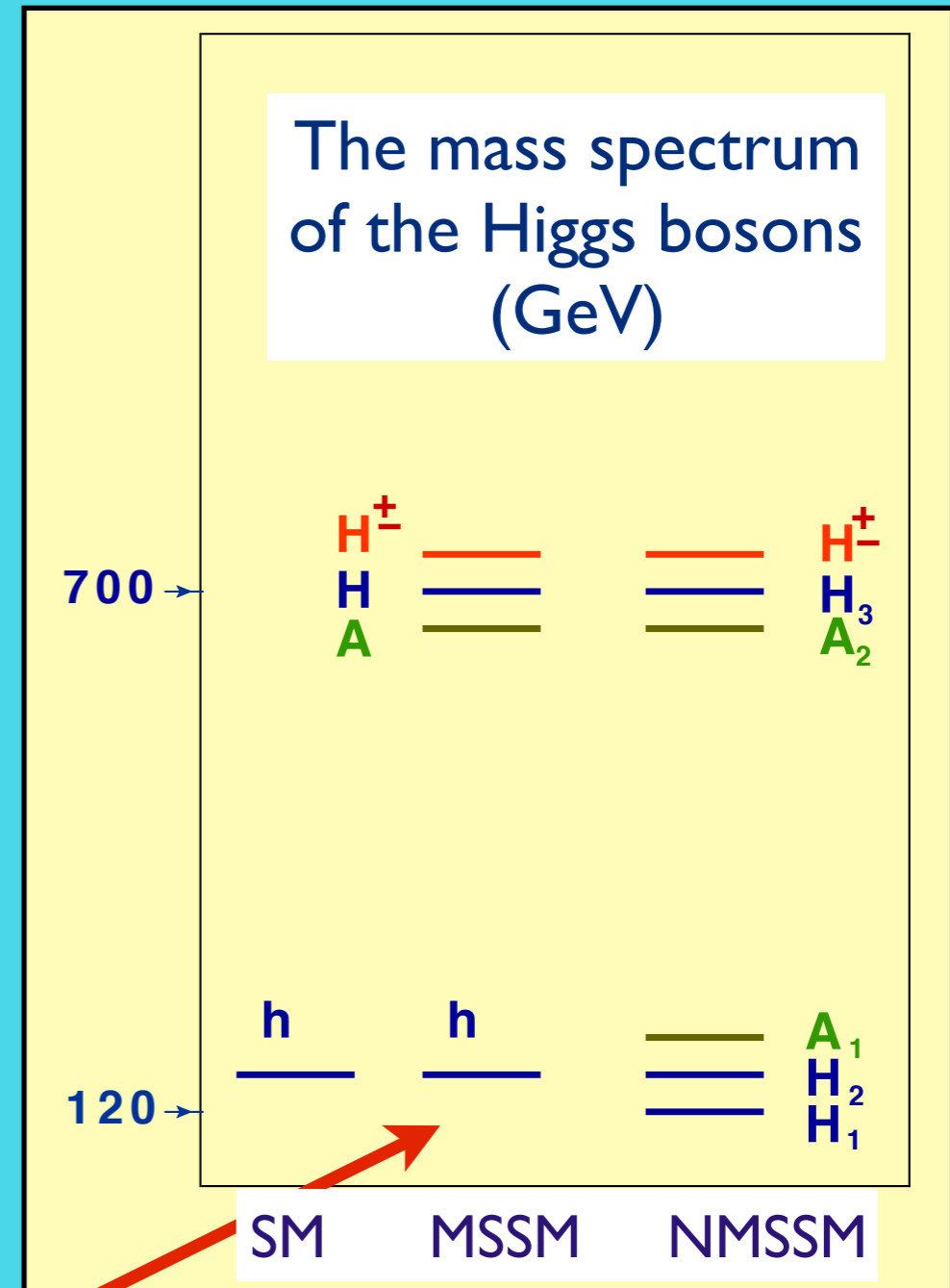
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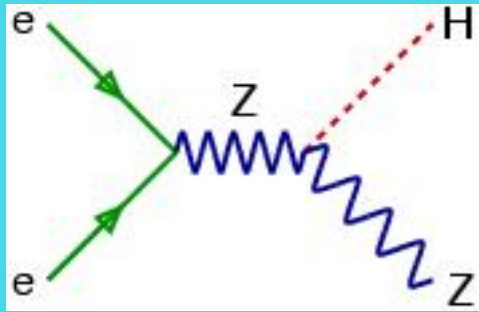
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One has to check the presence or absence of heavy Higgs bosons

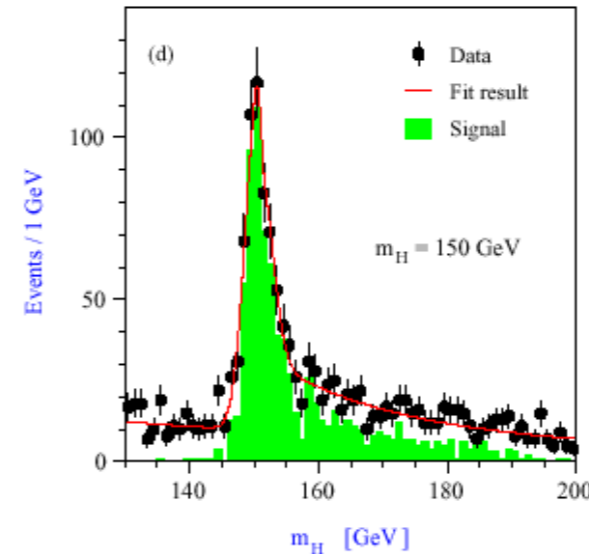
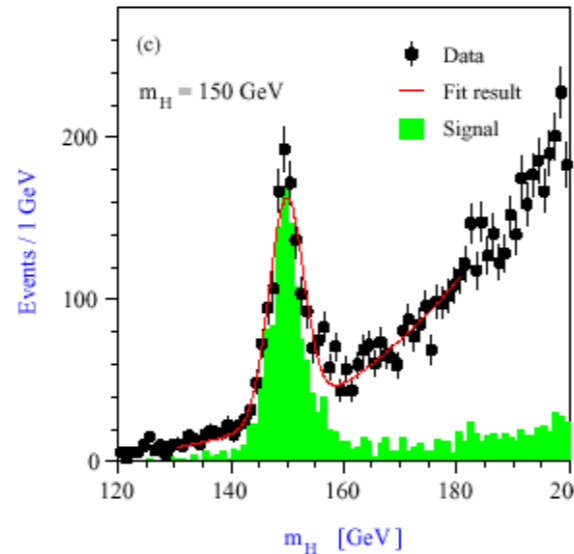
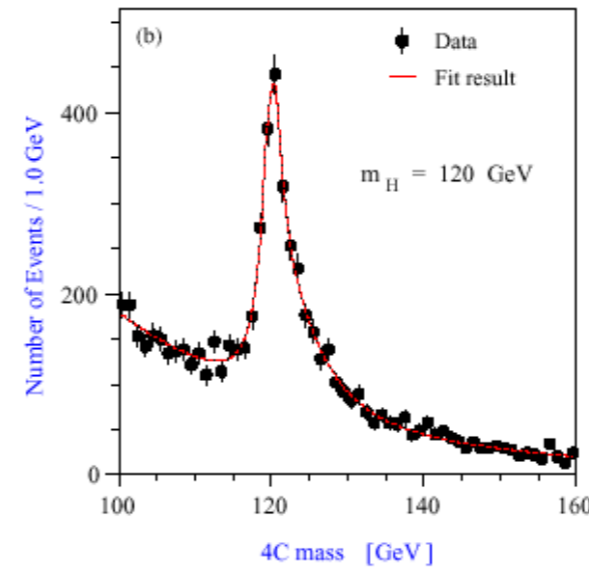
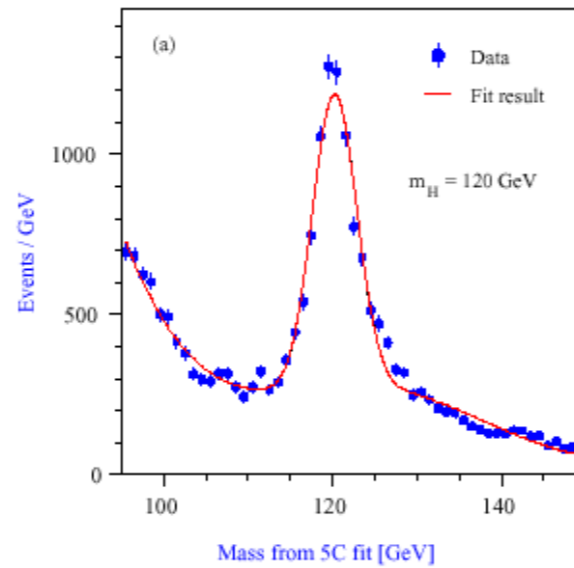
Precision Physics of the Higgs bosons



$$\rightarrow b\bar{b}q\bar{q}$$

$ee \rightarrow HZ$ diff. decay channels

$$\rightarrow W^+W^-q\bar{q}$$



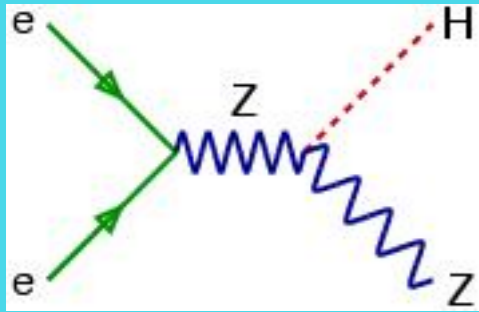
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$$\Delta m_H = 40 \text{ MeV}$$

$$\rightarrow W^+W^-l^+l^-$$

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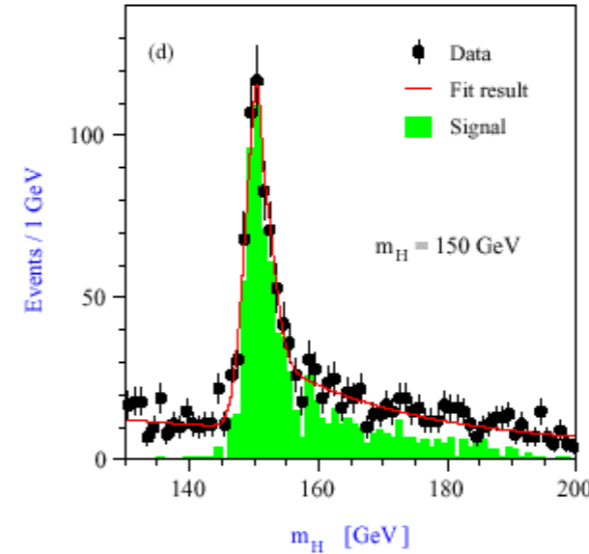
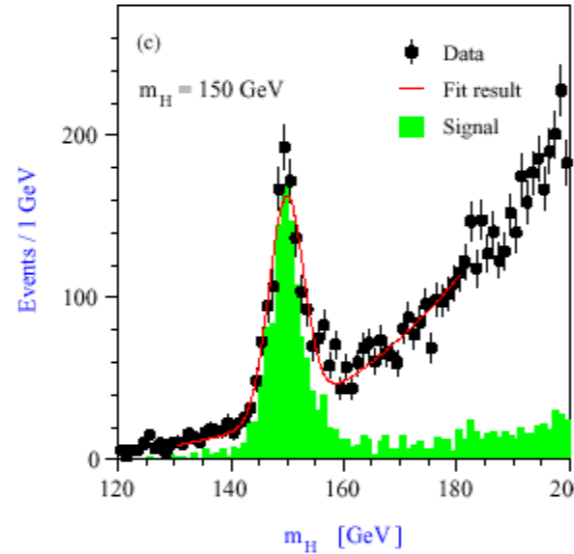
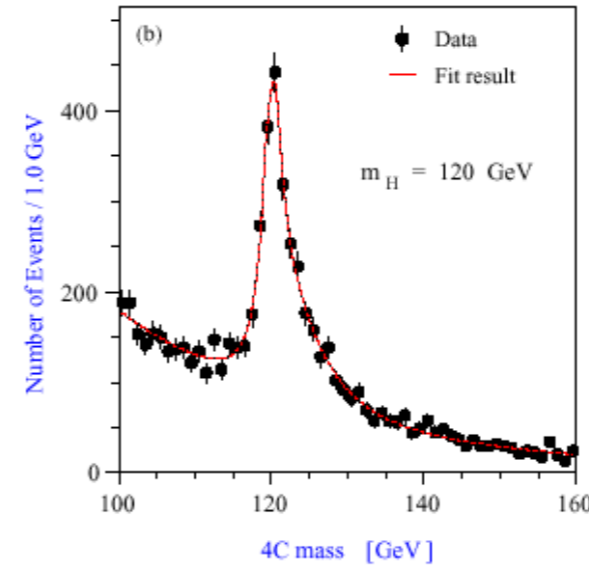
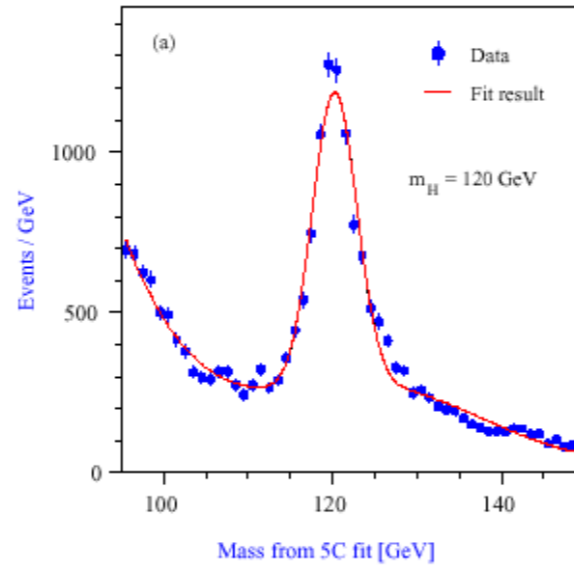


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Int Linear Collider

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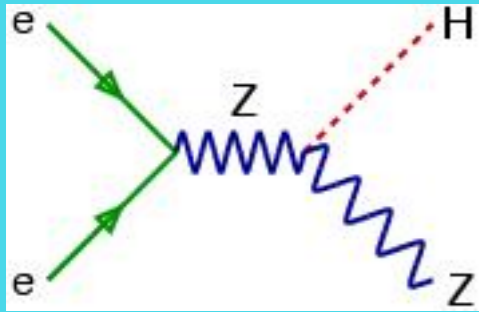
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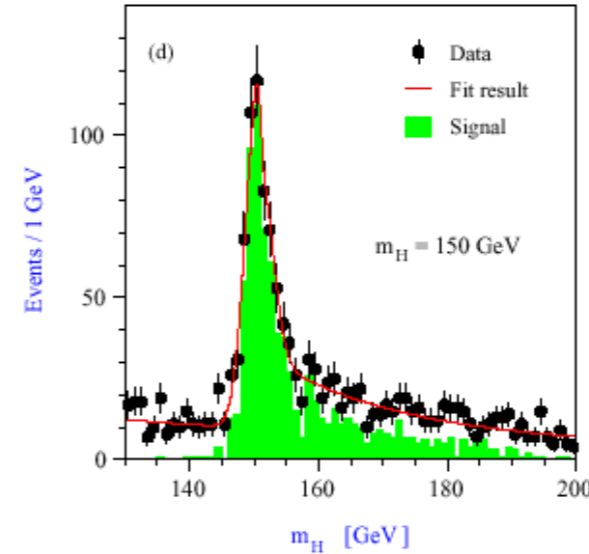
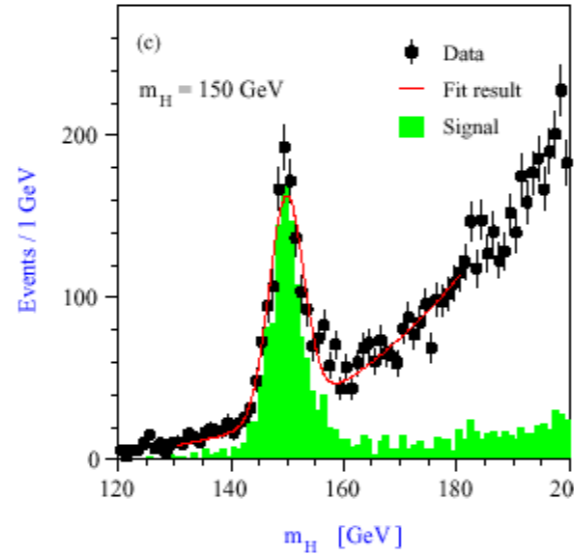
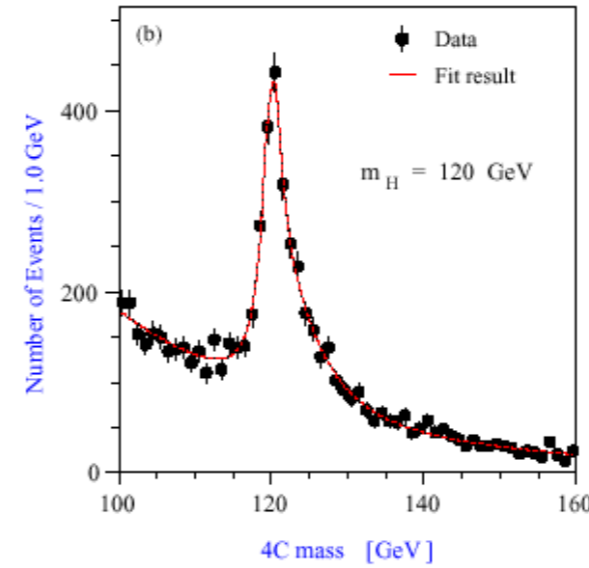
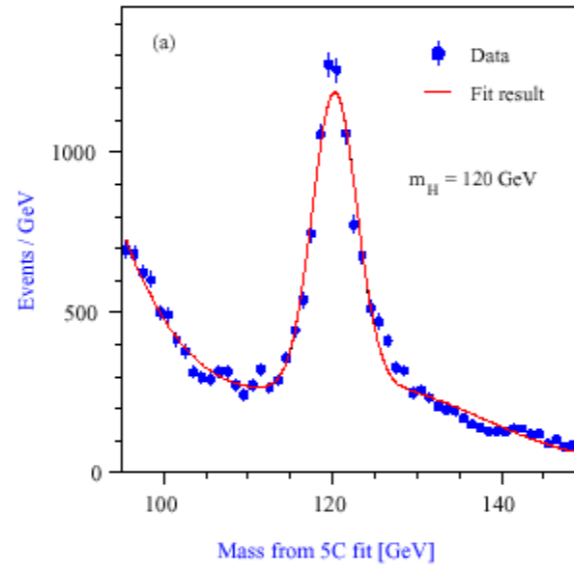


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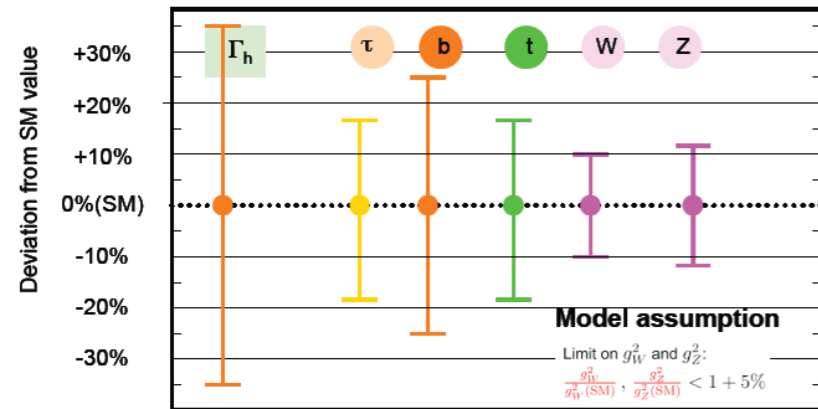
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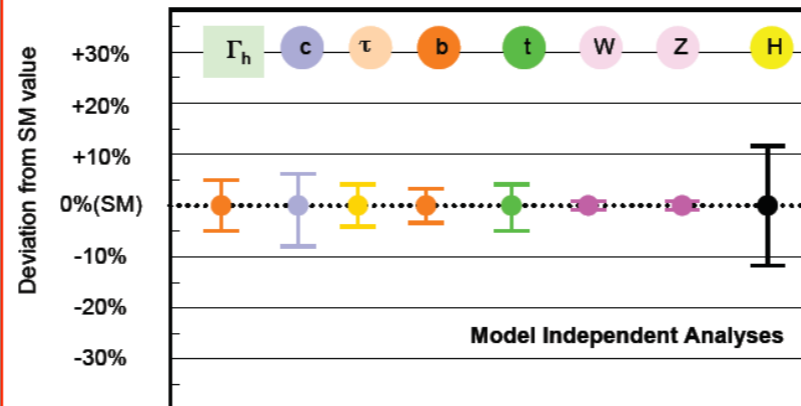
Coupling Precision

LHC $300 \text{ fb}^{-1} \times 2$

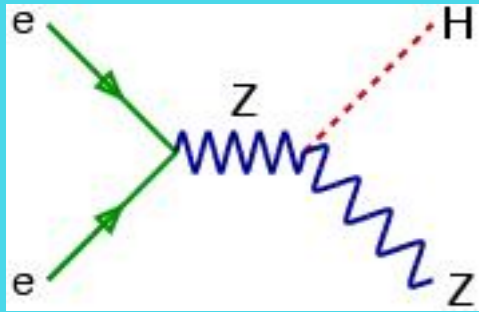


Coupling Precision

ILC



Precision Physics of the Higgs bosons

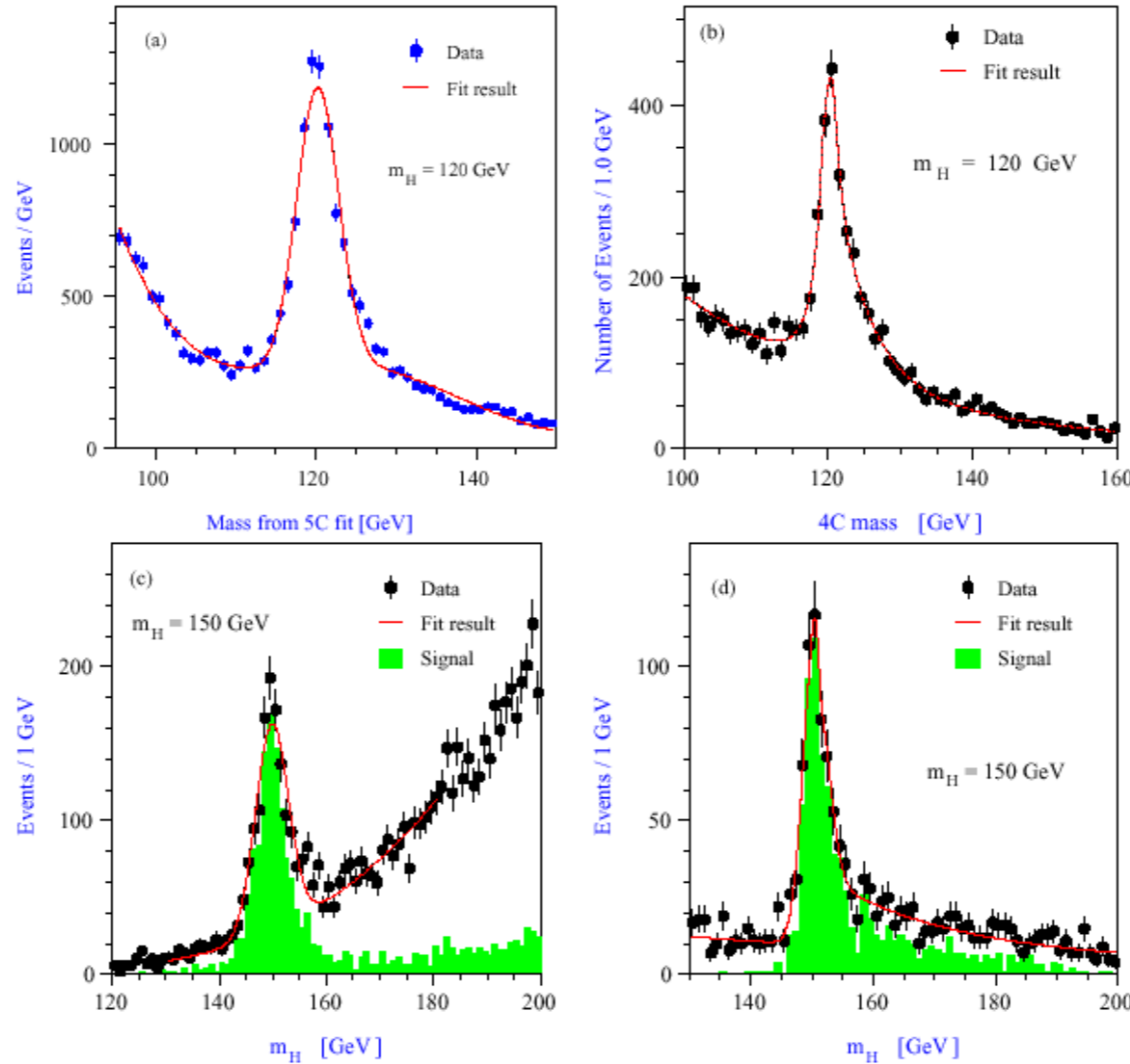


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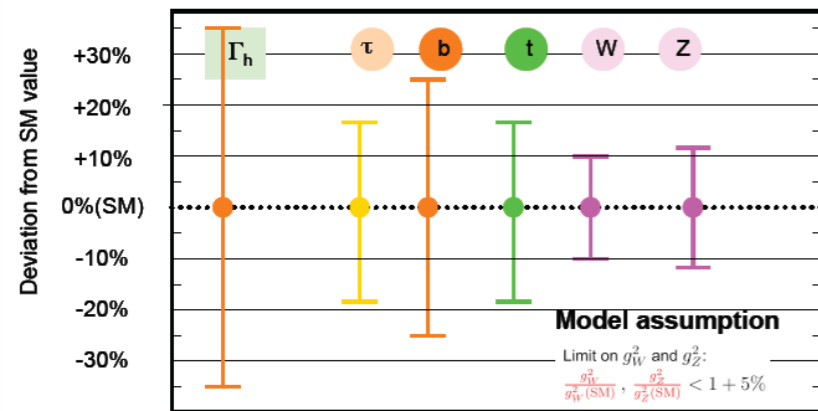
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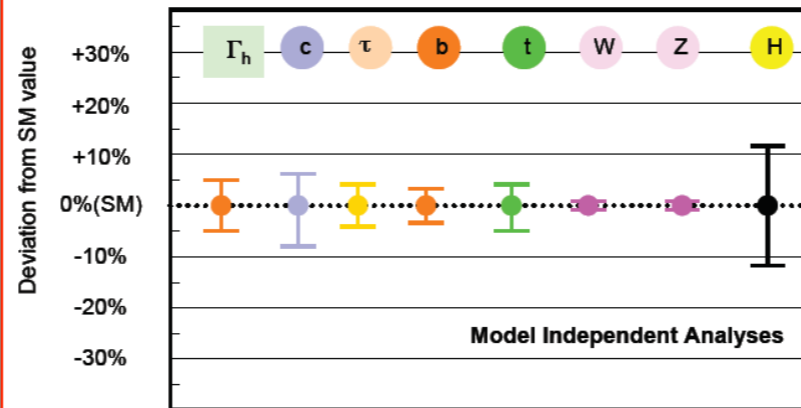
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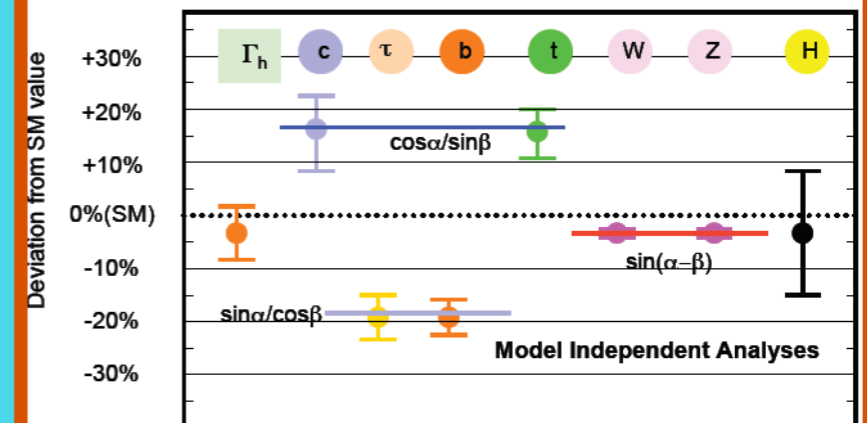
Coupling Precision

ILC



SUSY or 2HDM

ILC



The Mass Spectrum and Mixing

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$$m_{quark} = y_{quark} \cdot v$$

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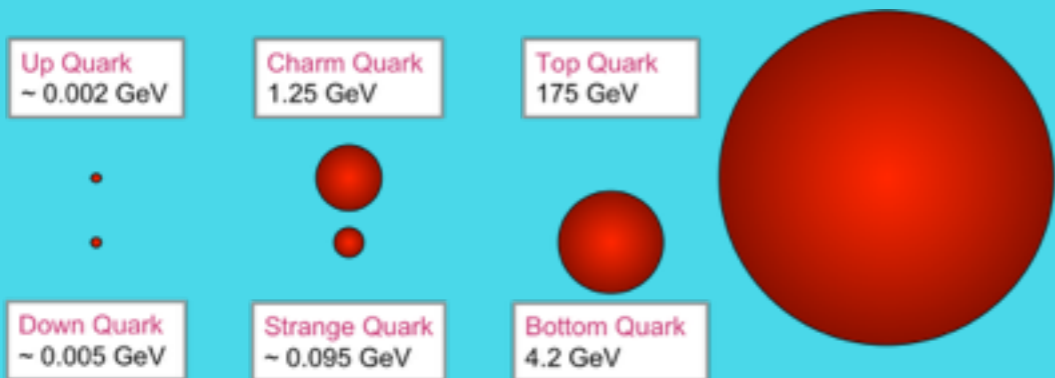
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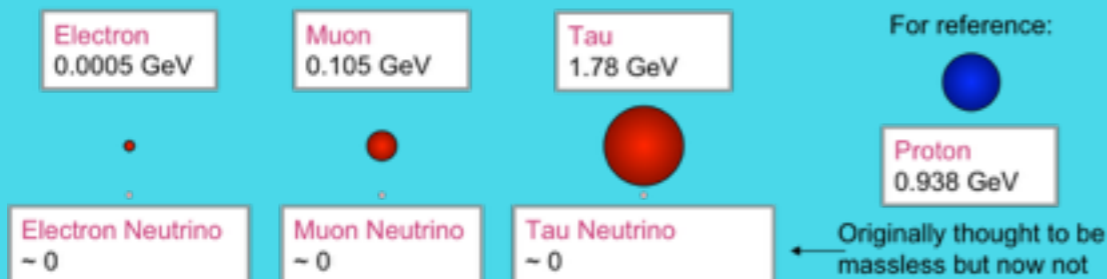
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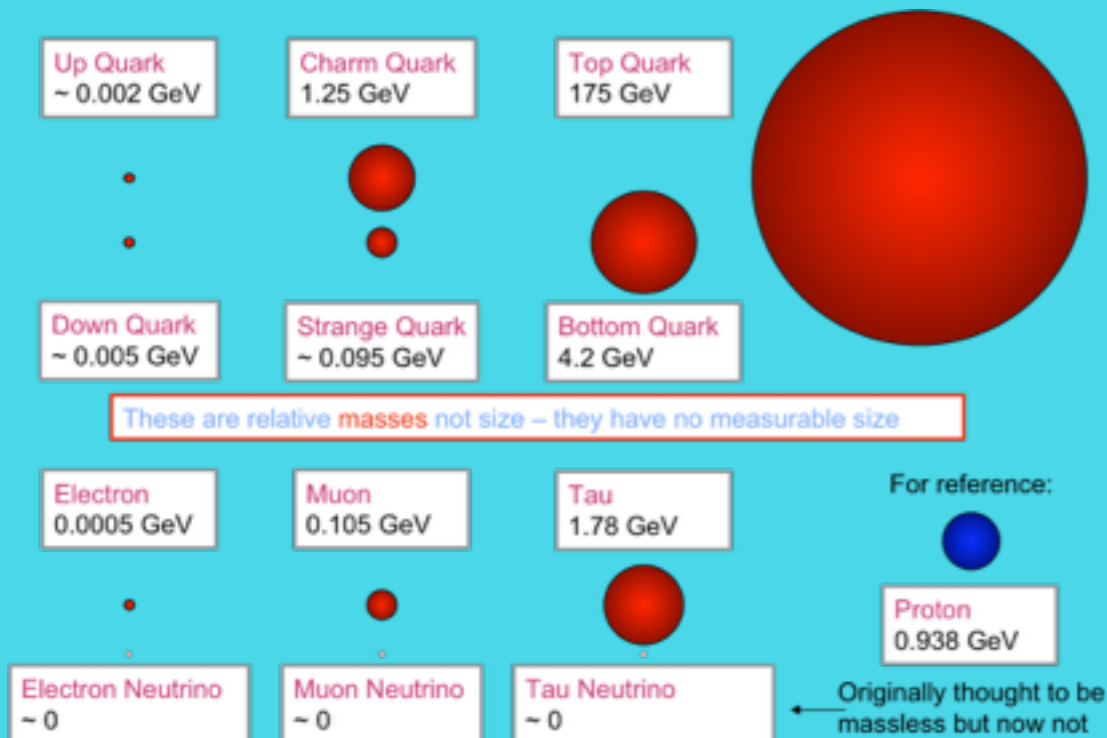
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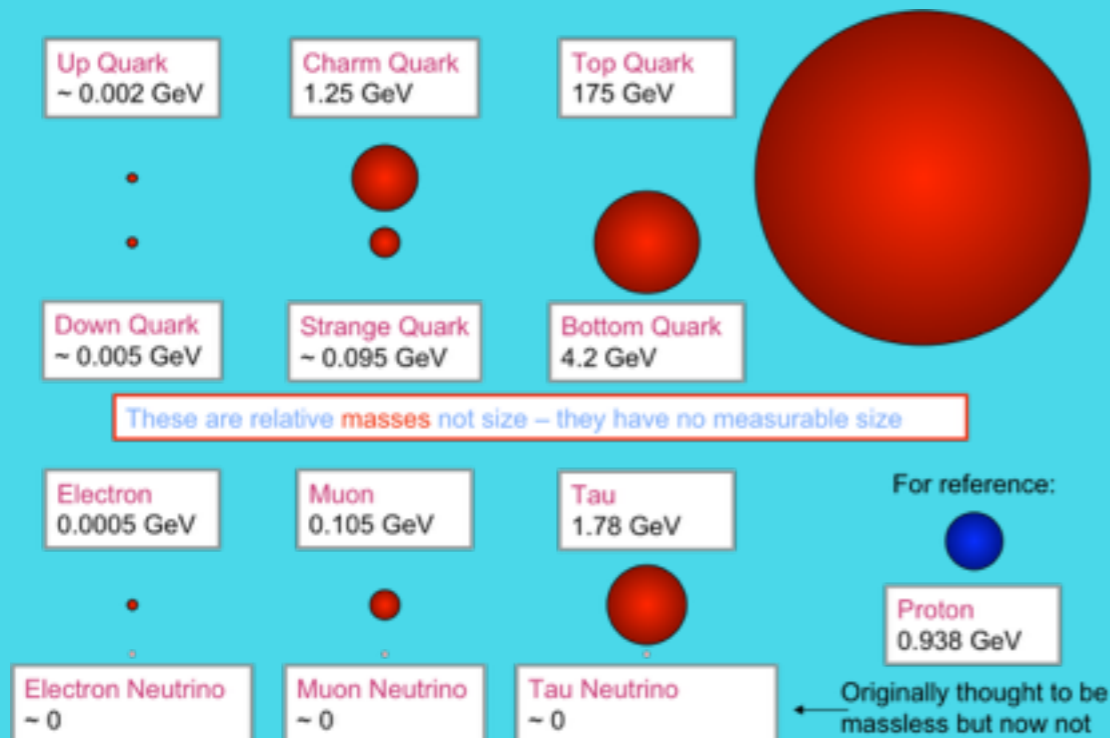
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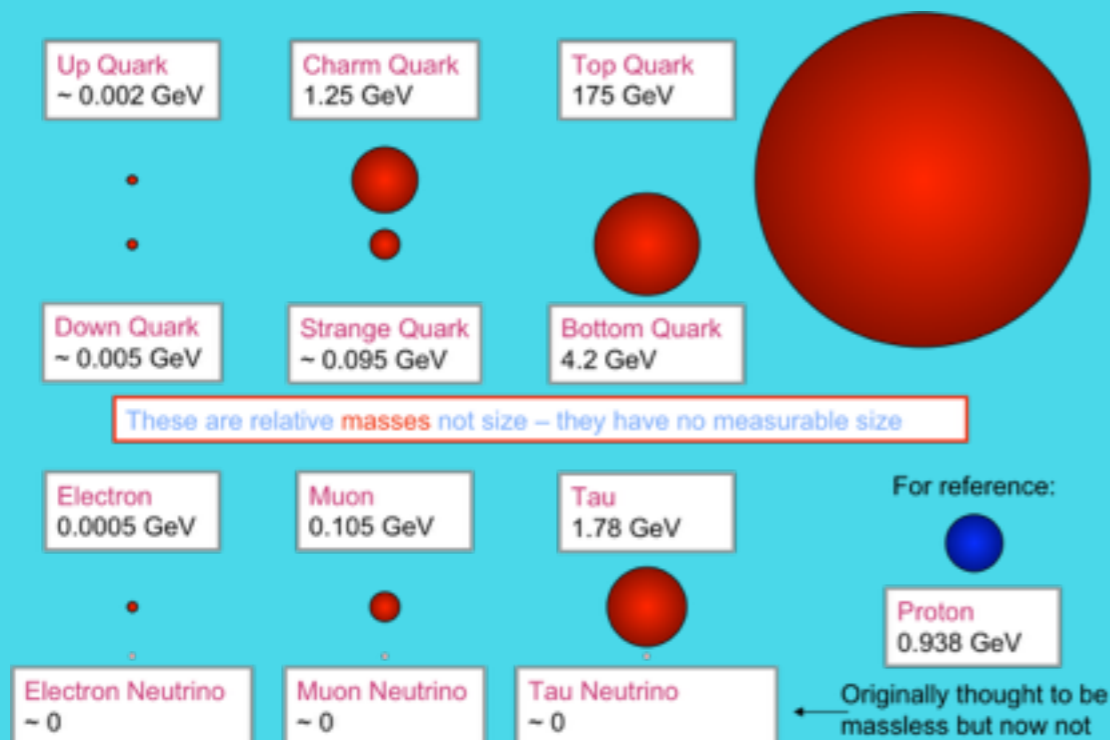
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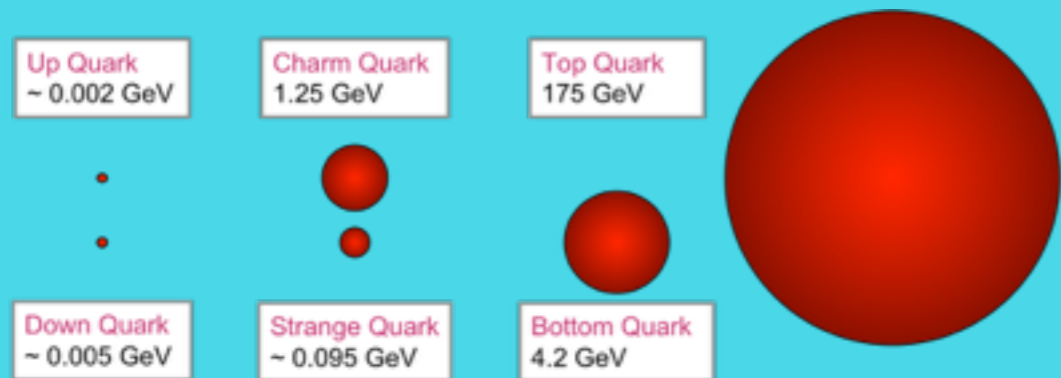
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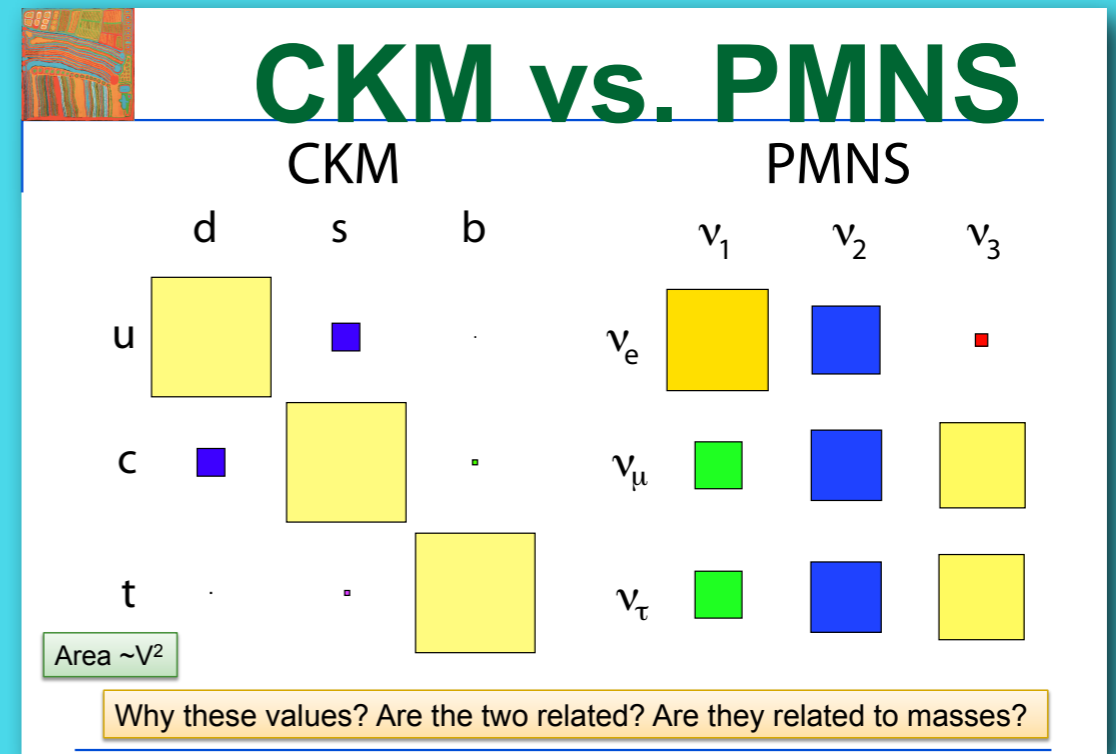


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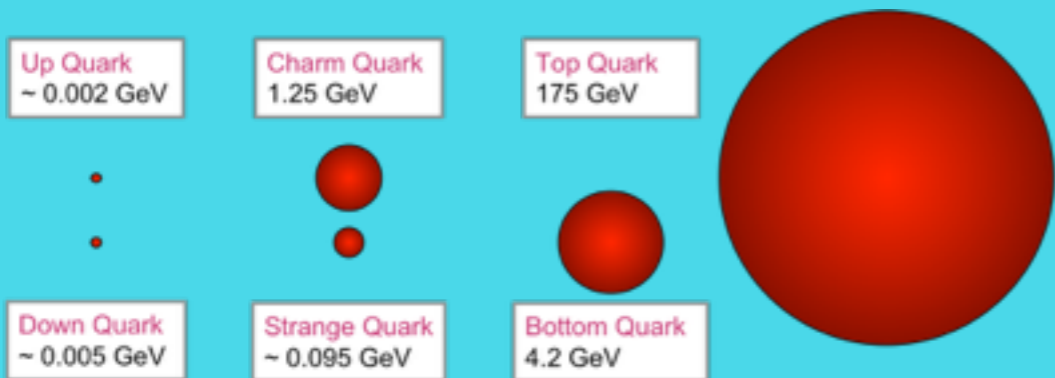
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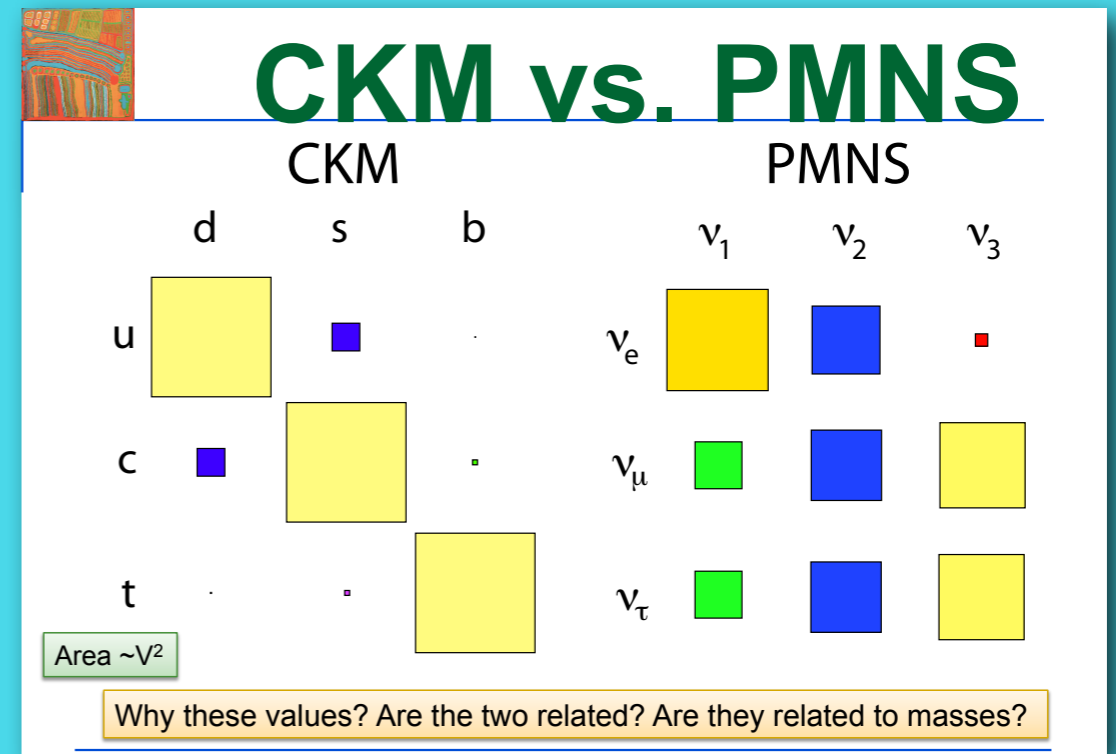


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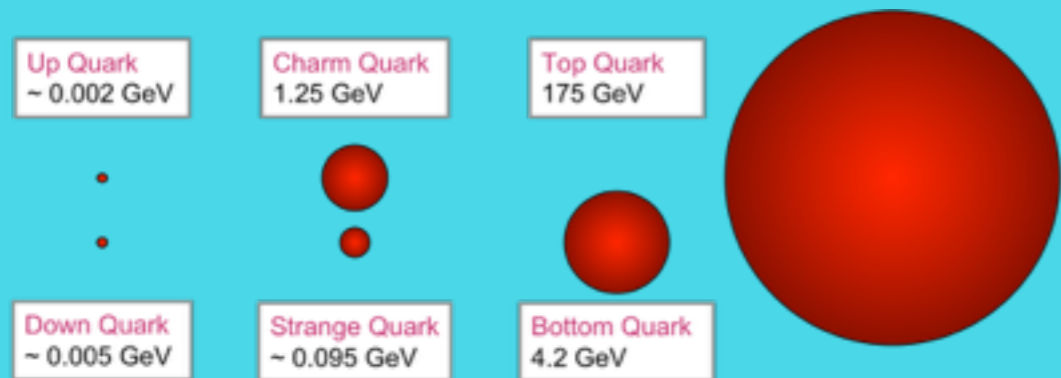
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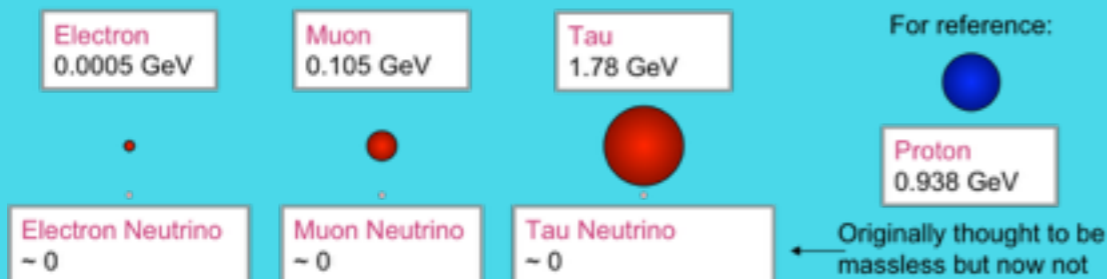
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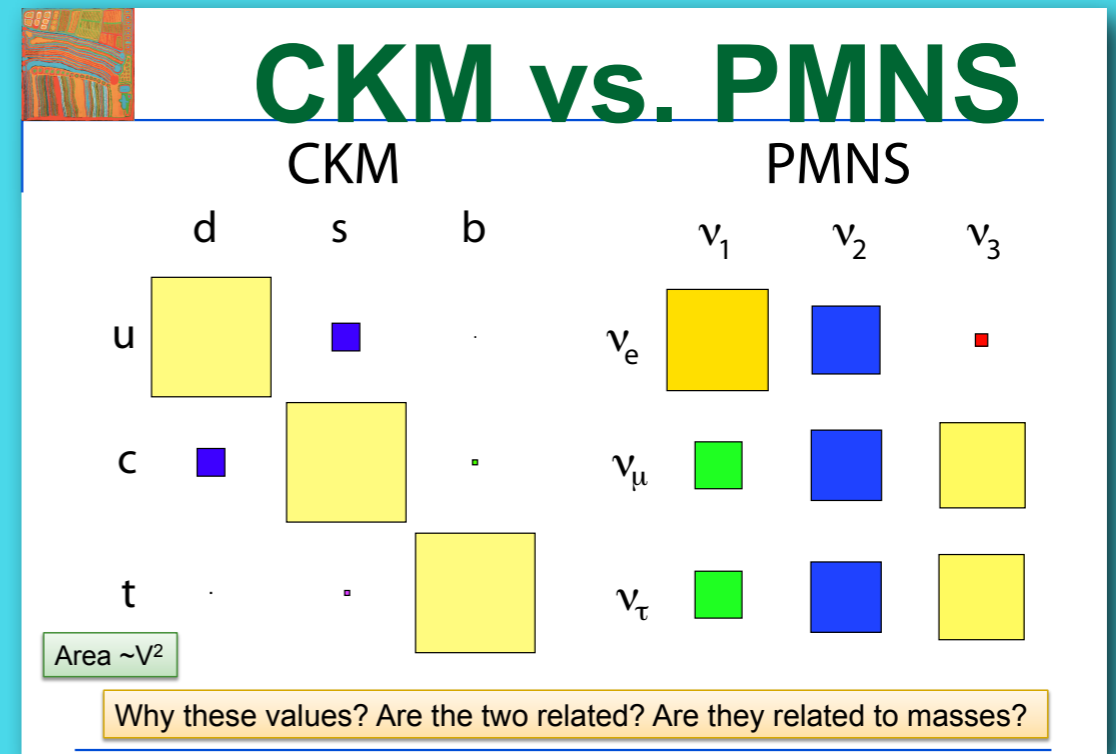


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- What re the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

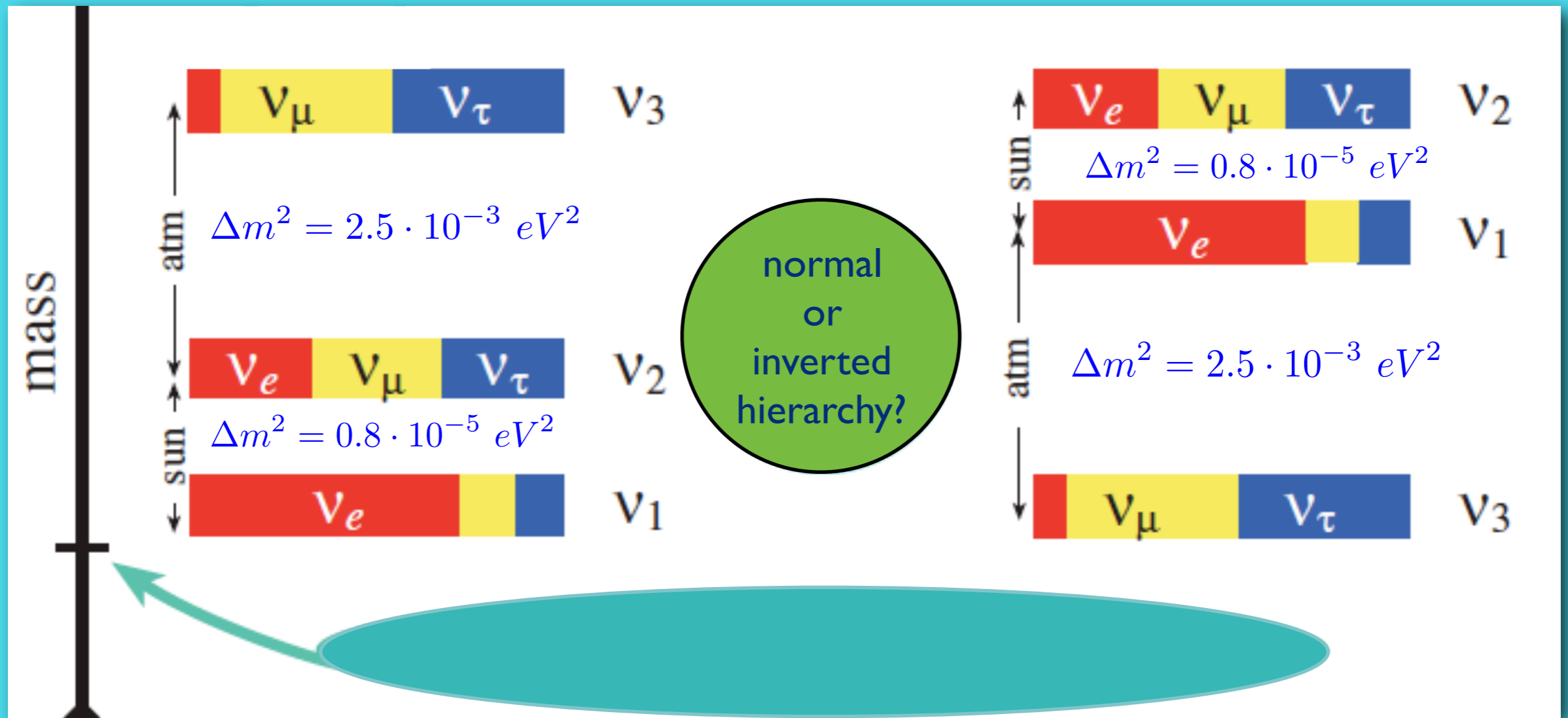
Neutrino Sector

Neutrino Sector

Neutrino masses

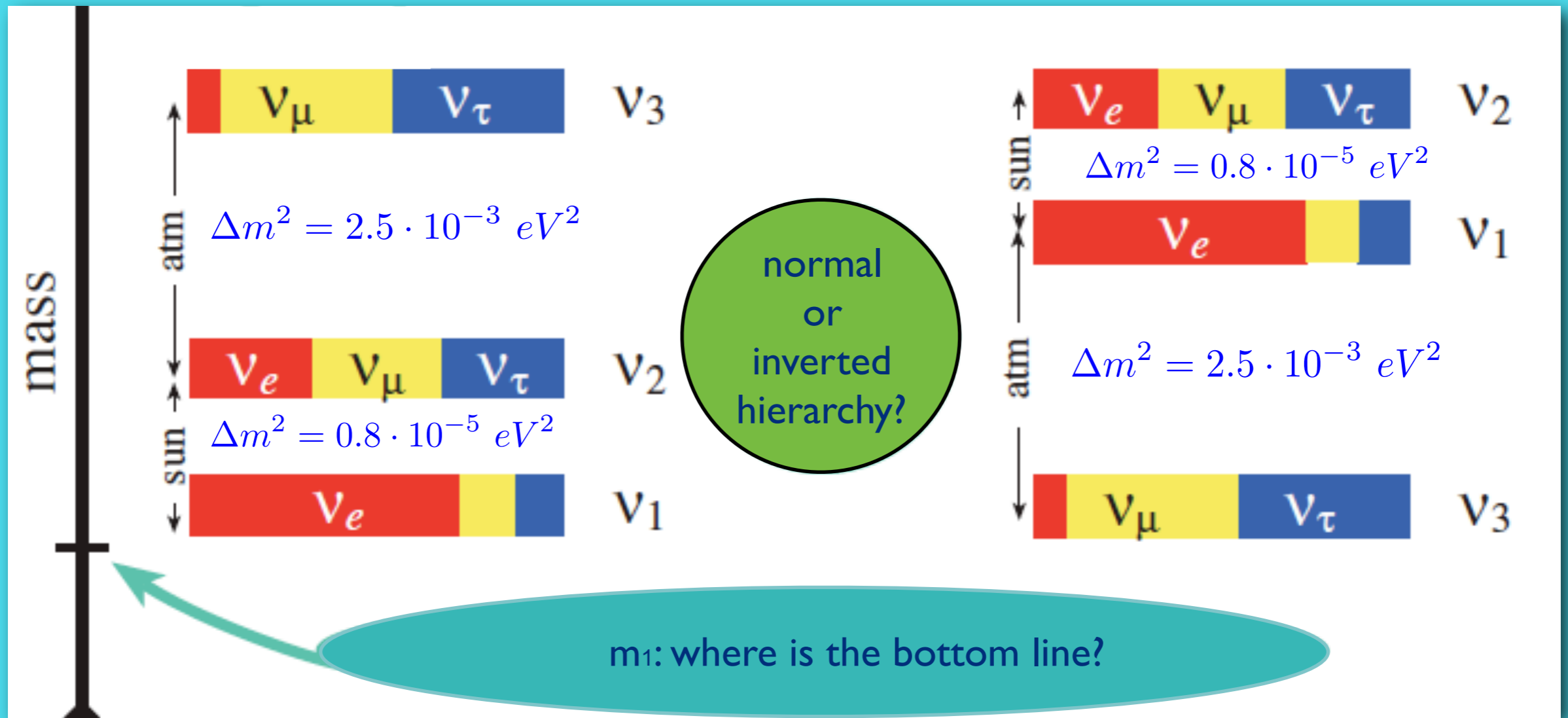
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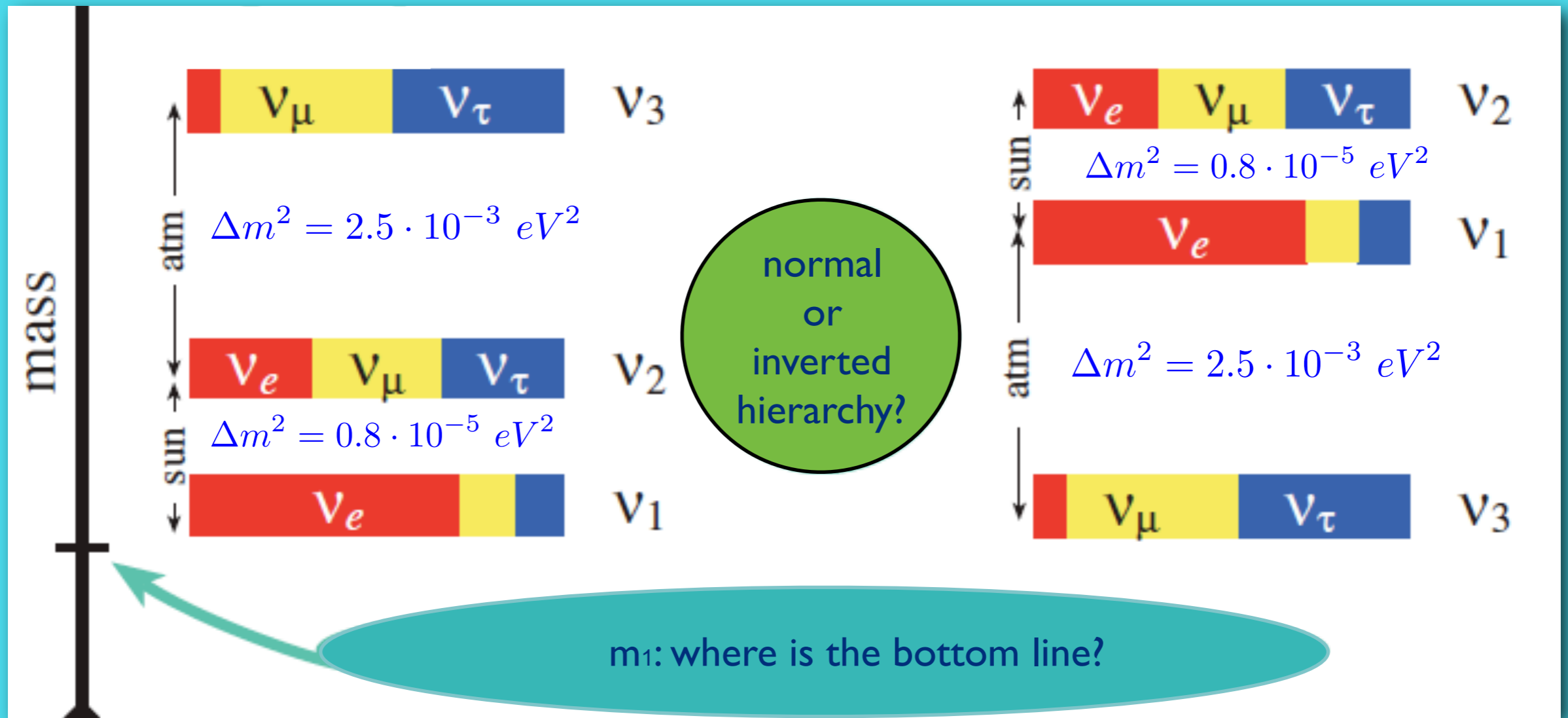
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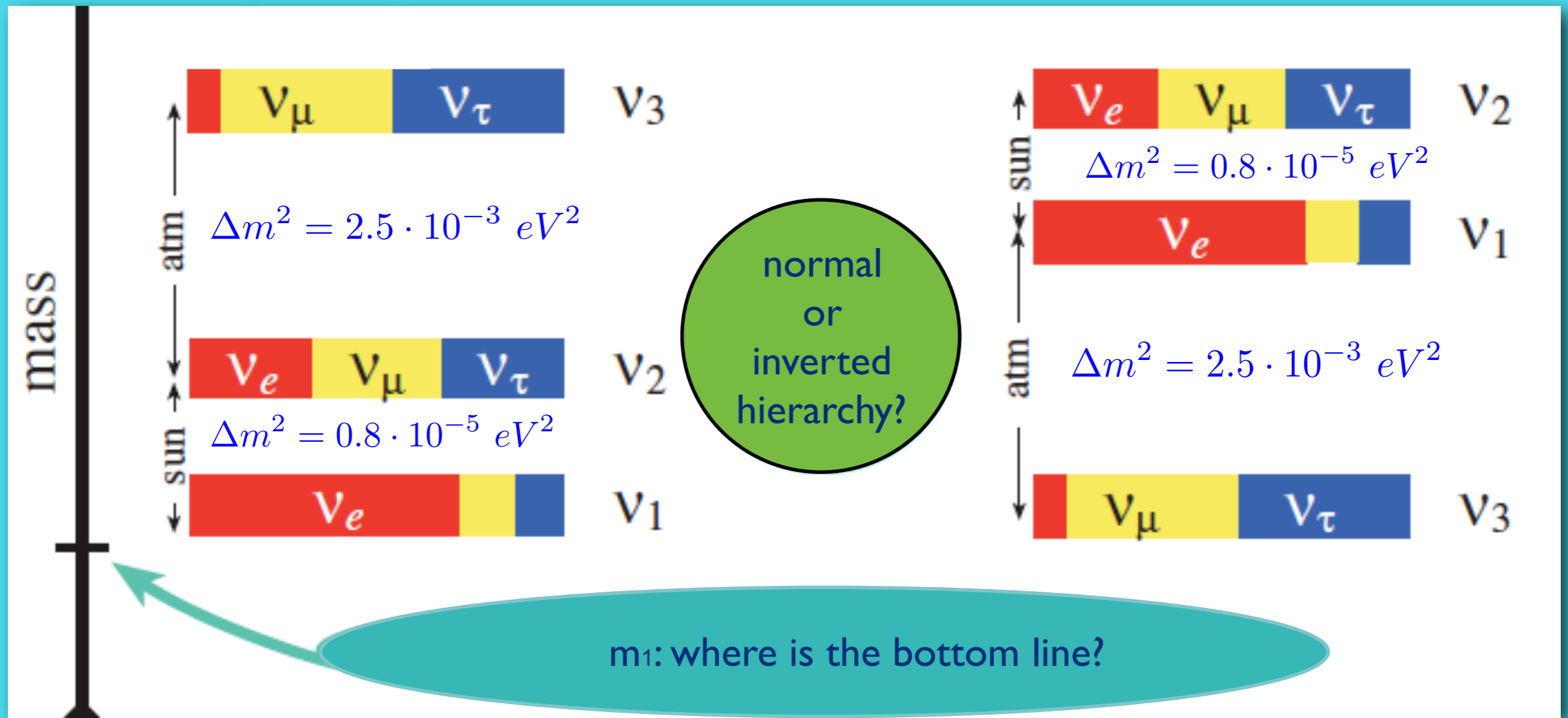
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cosmology: the CMB spectrum

Planck

Neutrino Sector

Neutrino masses



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cosmology: the CMB spectrum

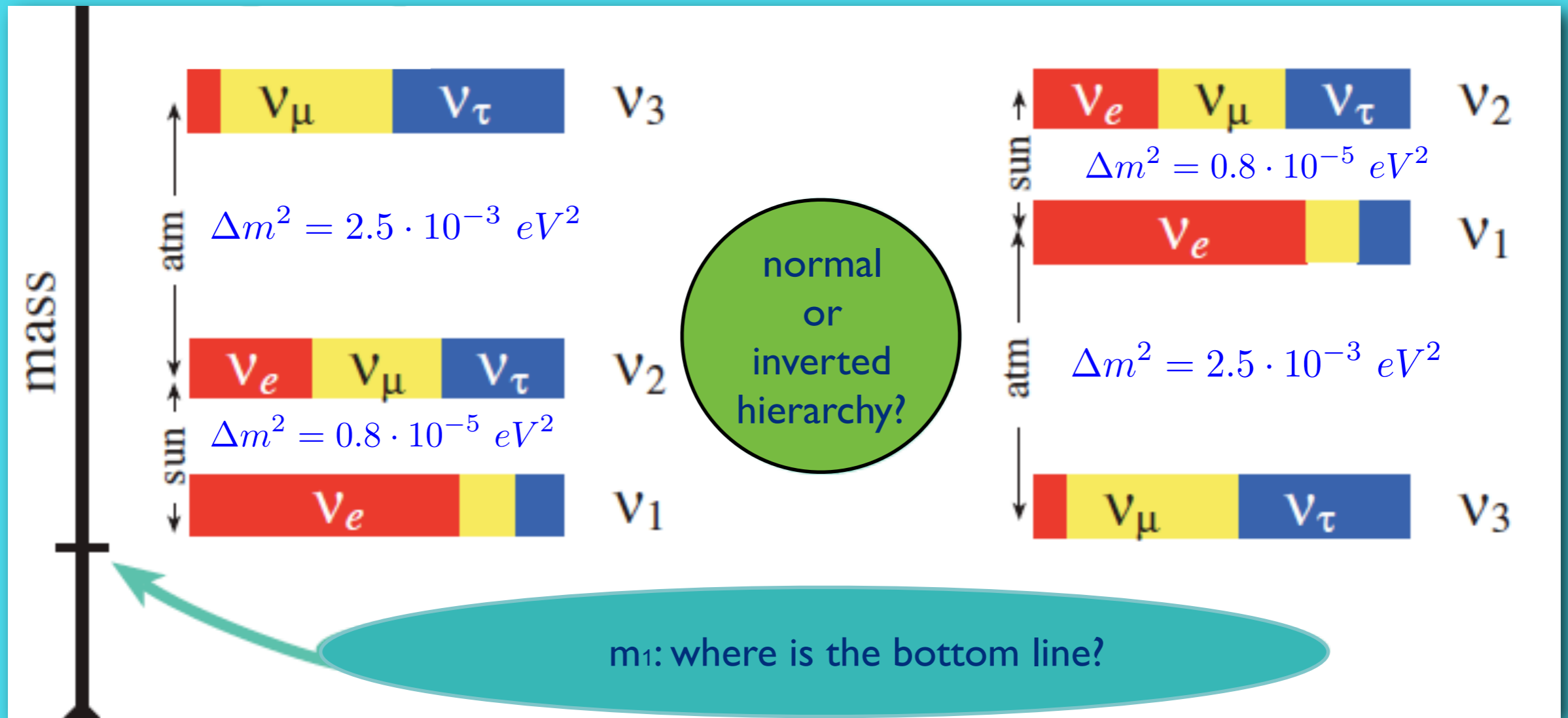
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β -decay
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KATRIN

Neutrino Sector

Dirac or Majorana?

$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

Neutrino Sector

Dirac or Majorana?

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$0\nu\beta\beta$ decay

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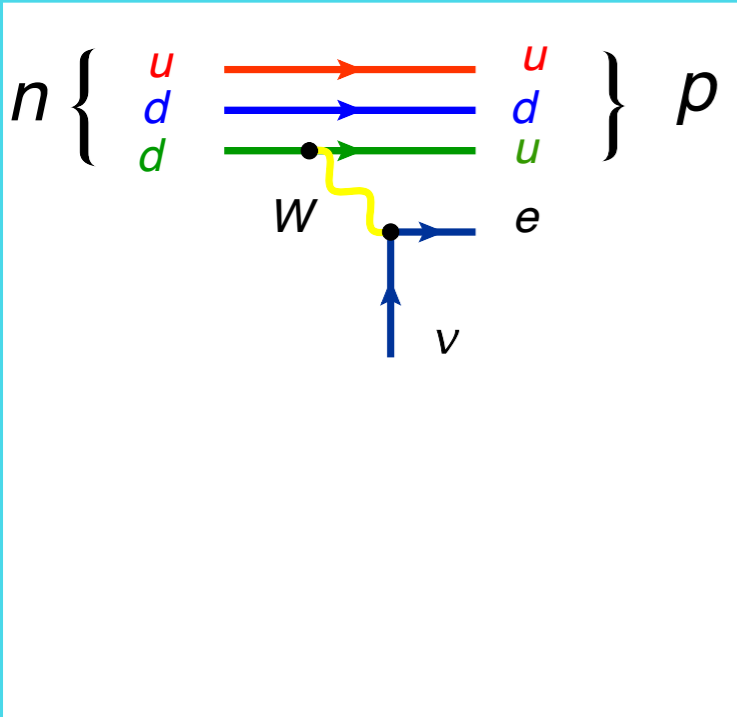
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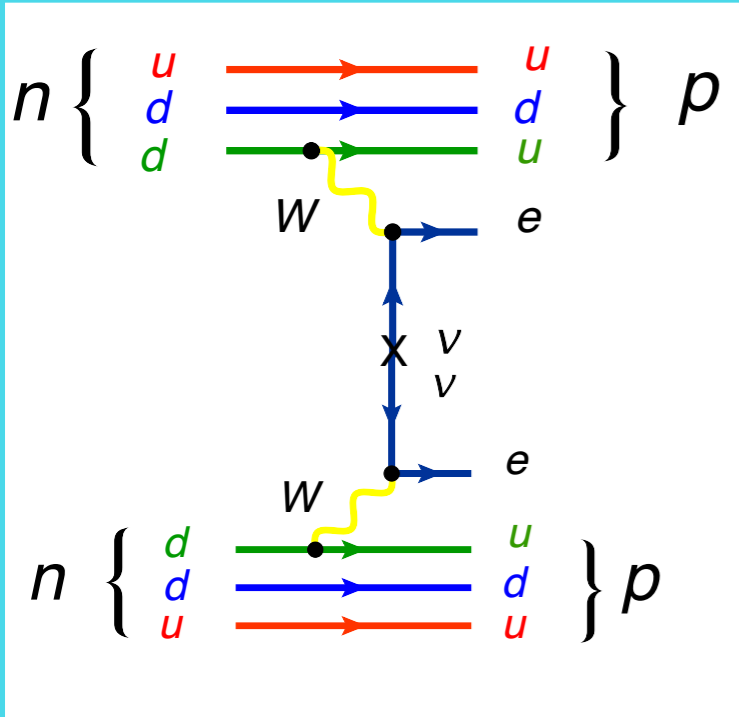
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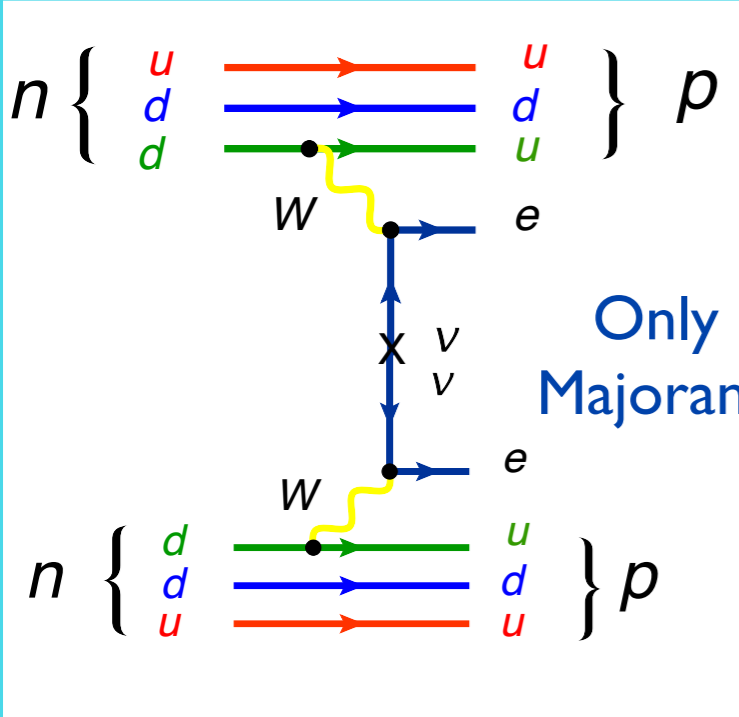
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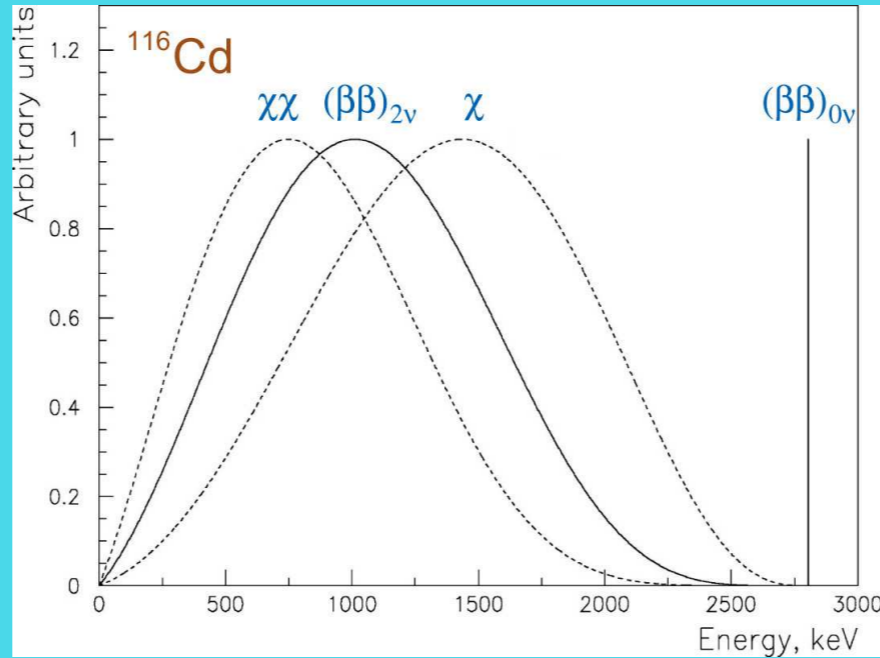
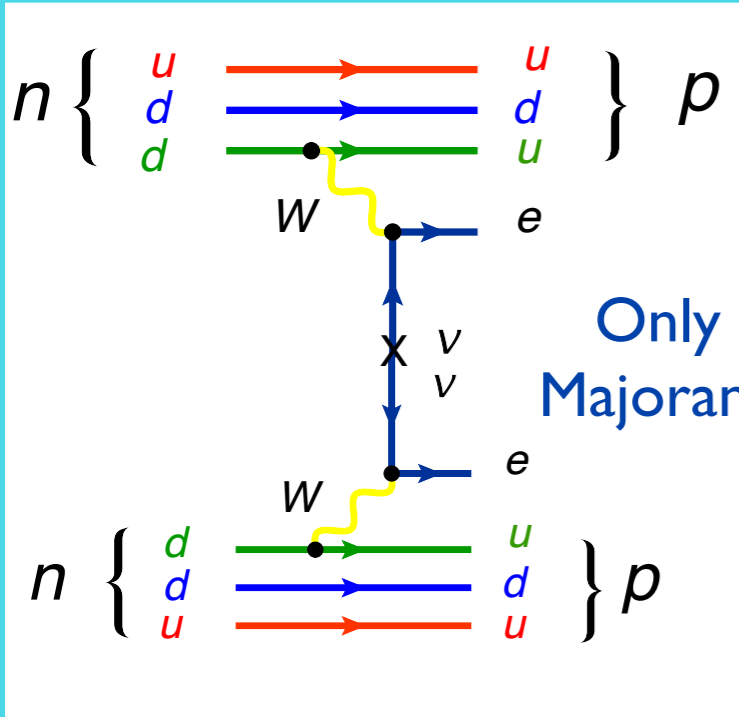
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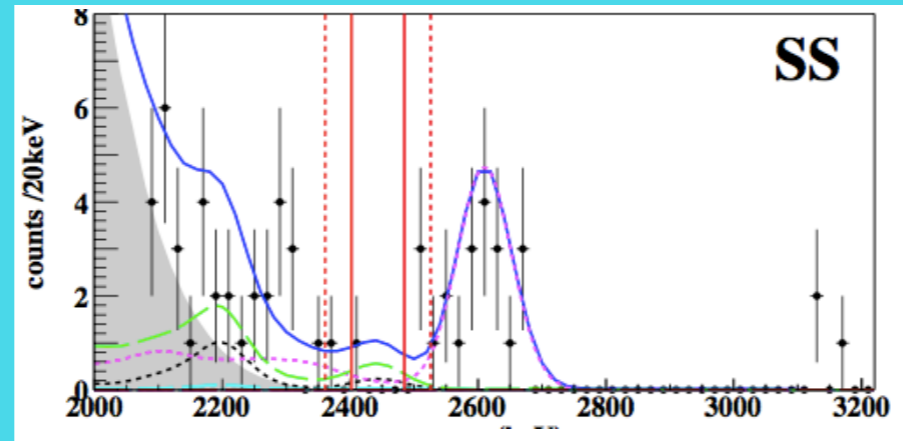
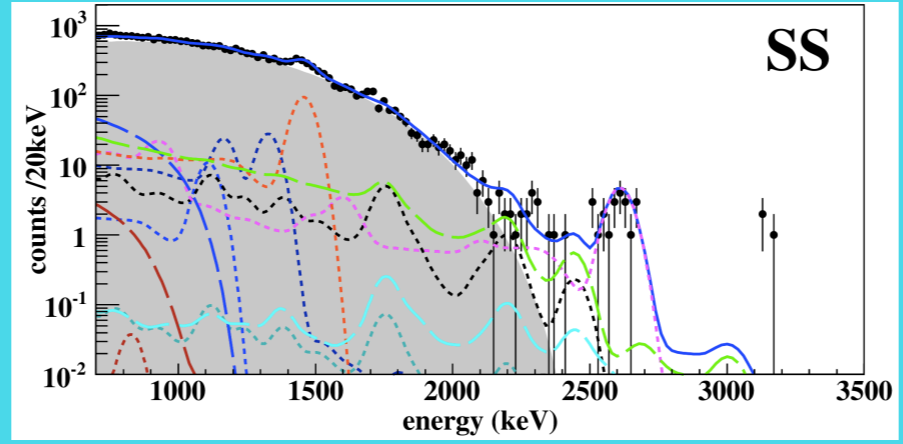
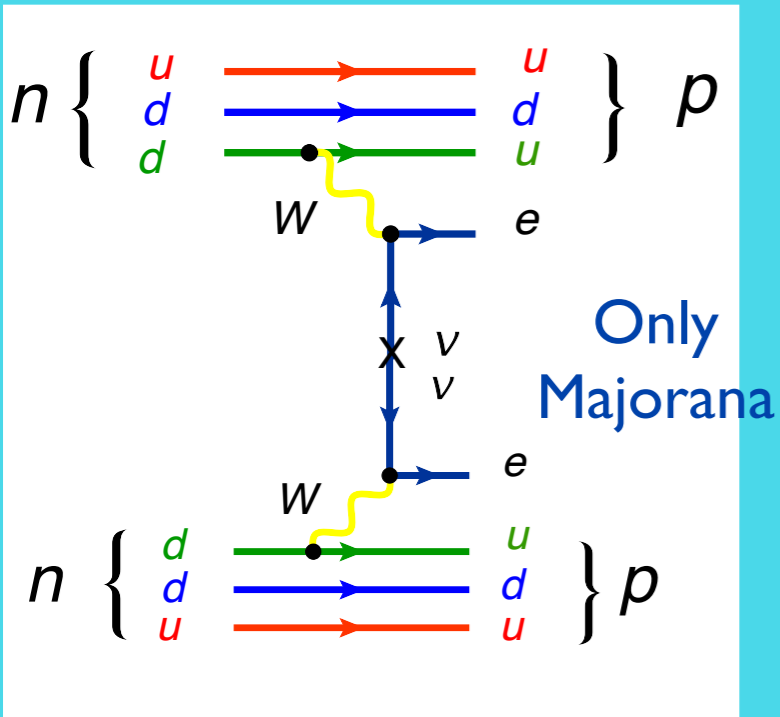
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Candidate Isotope	Experiment
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⁸² Se	SuperNemo, Lucifer
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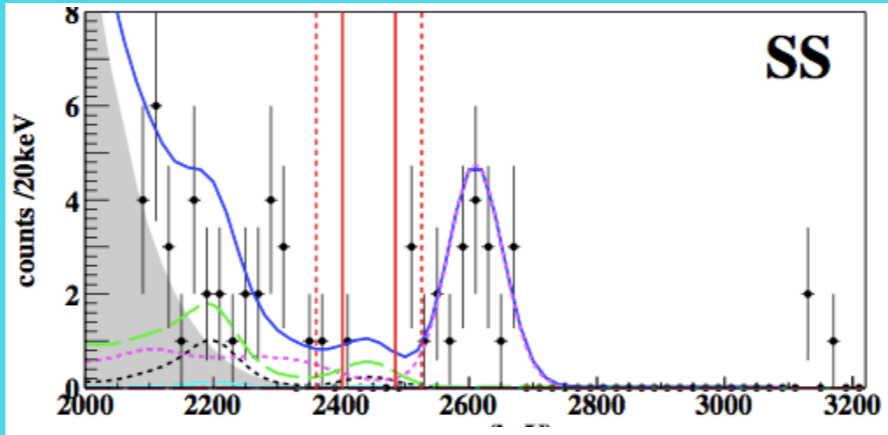
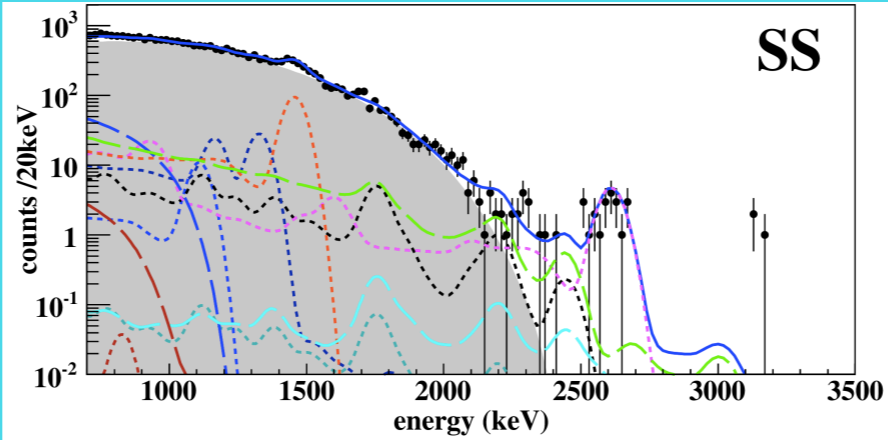
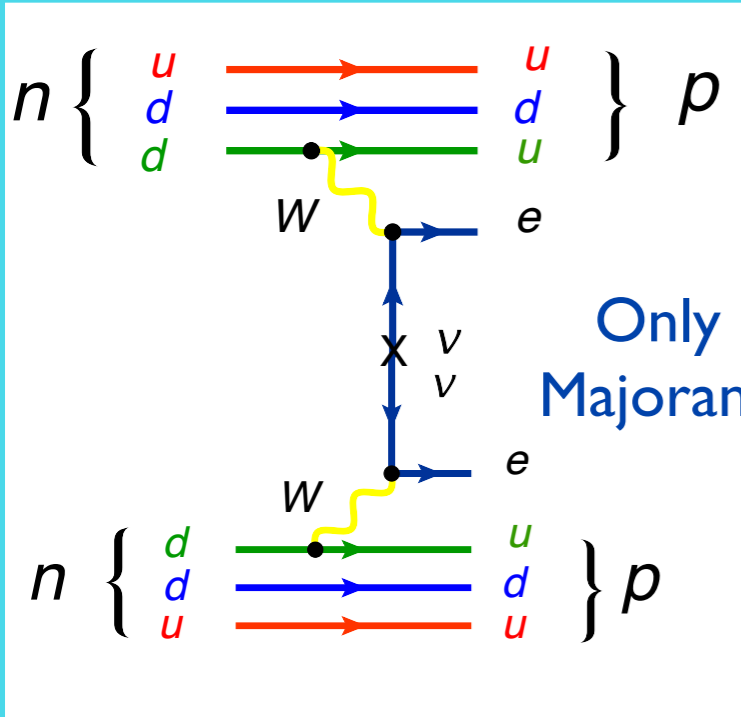
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$$T_{1/2}^{2\nu\beta\beta} (^{136}\text{Xe}) \times 10^{21} \text{ yr} = 2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}$$

Neutrino Sector

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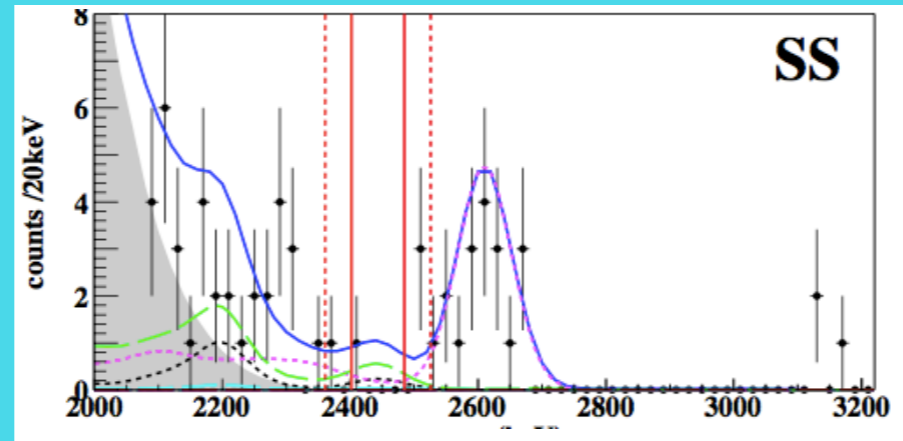
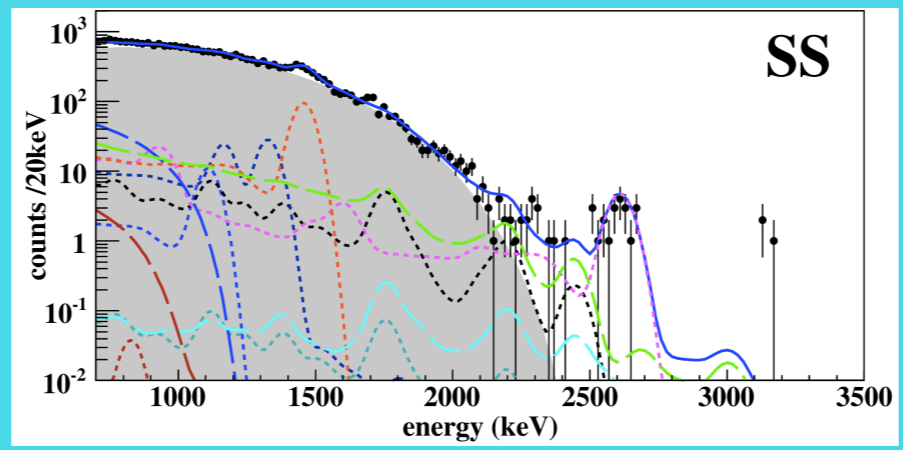
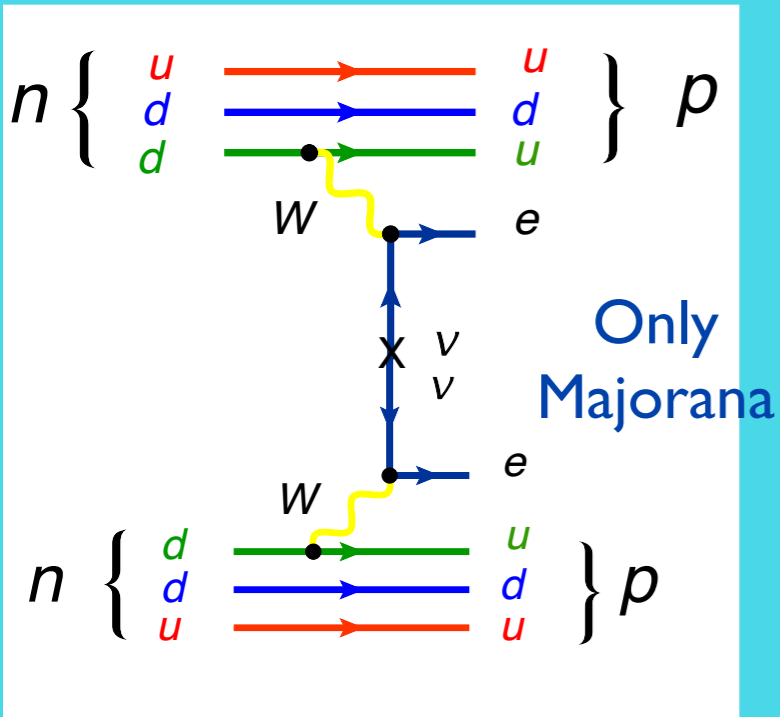
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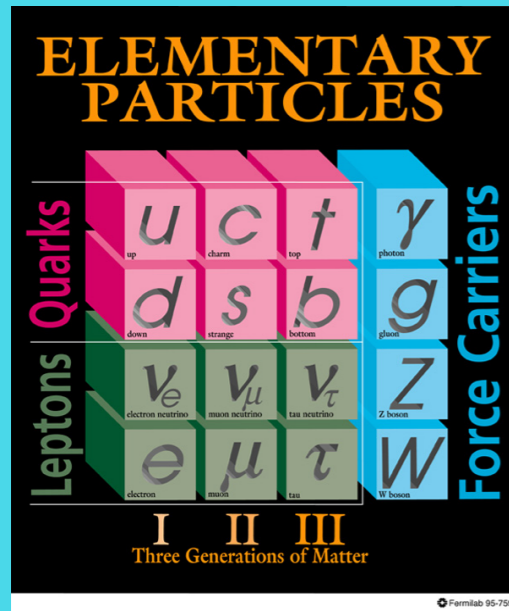
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$$T_{1/2}^{0\nu\beta\beta} (^{136}\text{Xe}) \times 10^{25} \text{ yr} > 1.6 \text{ (90\% CL)}$$

Flavour Sector

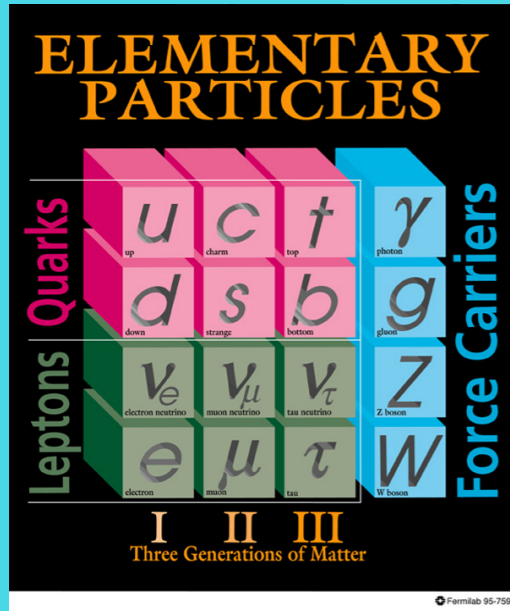
Flavour Sector

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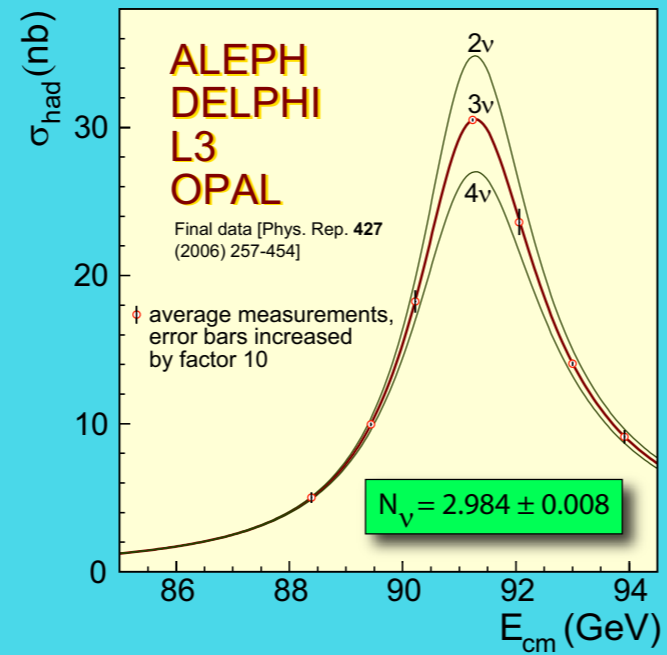


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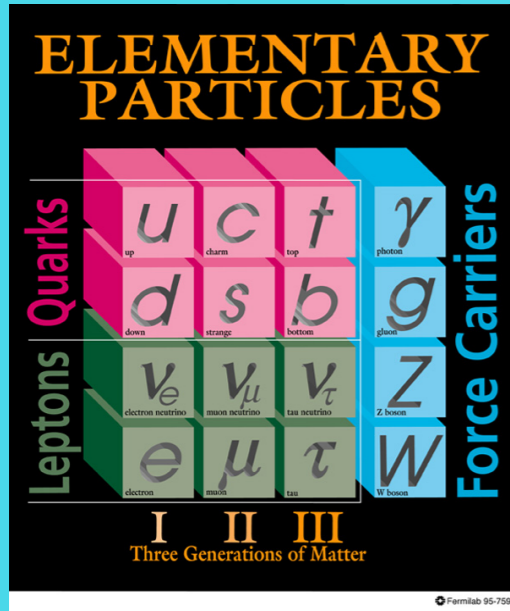


- The width of the Z-boson (LEP)

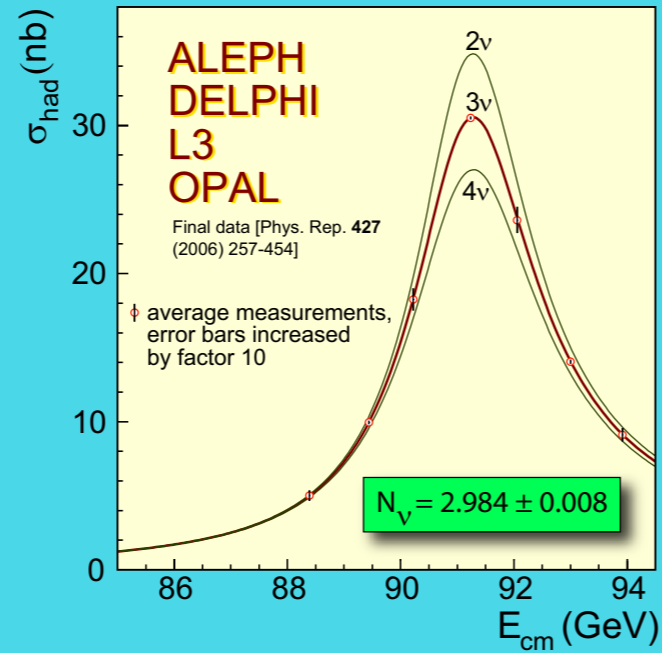


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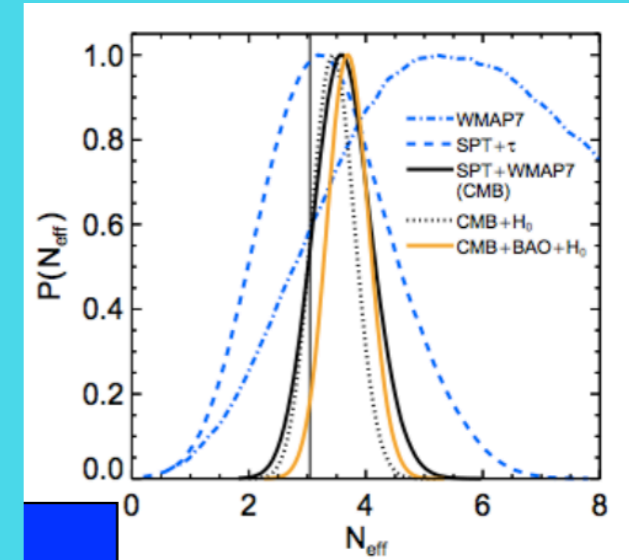
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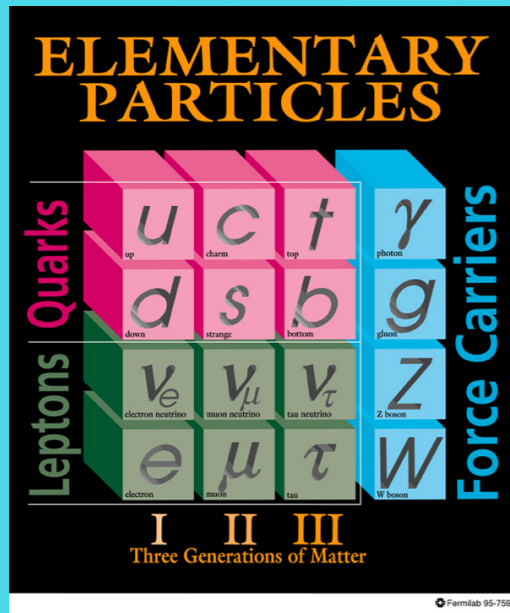


- The CMB spectrum (Planck)

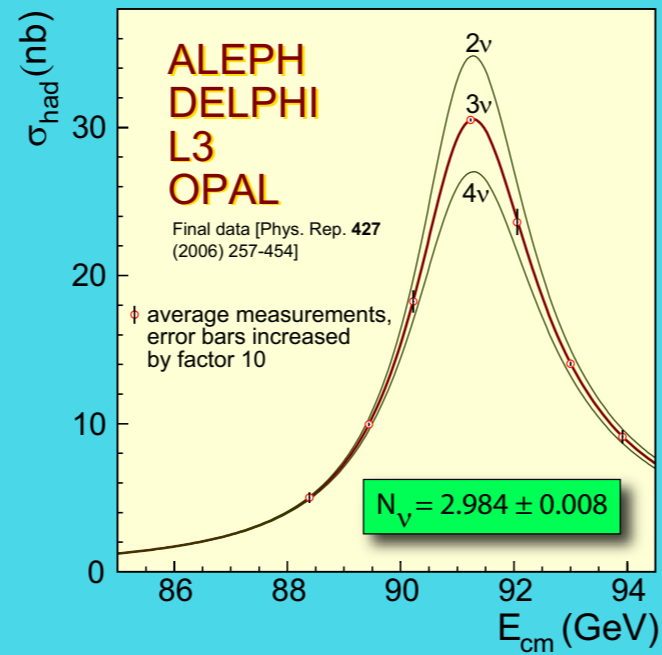


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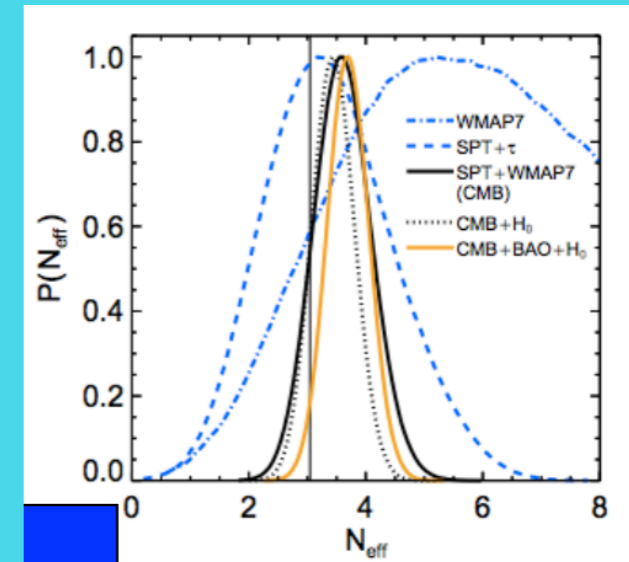
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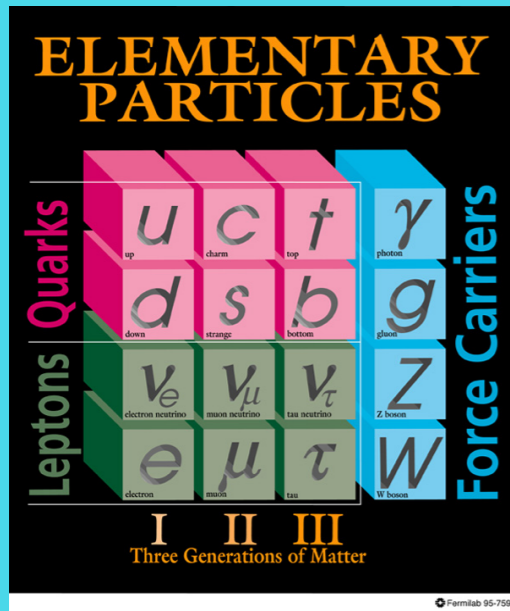


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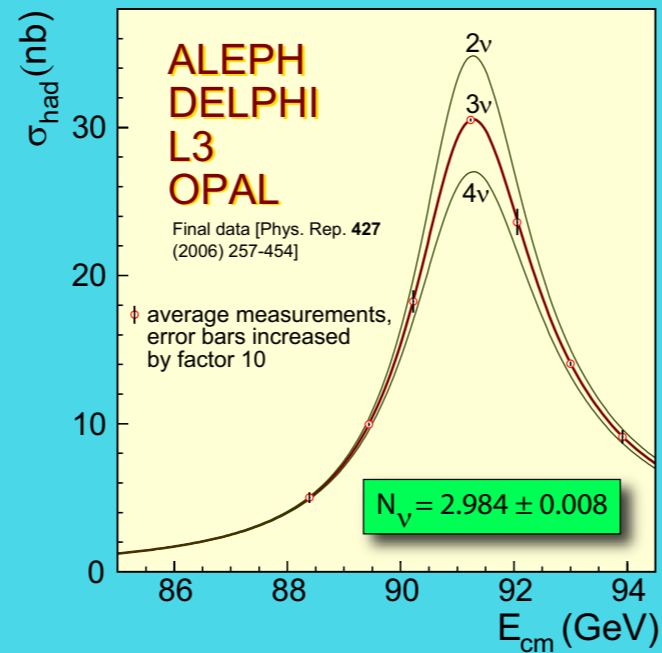
$$N_\nu^{eff} = 3.52 \pm 0.47$$

Flavour Sector

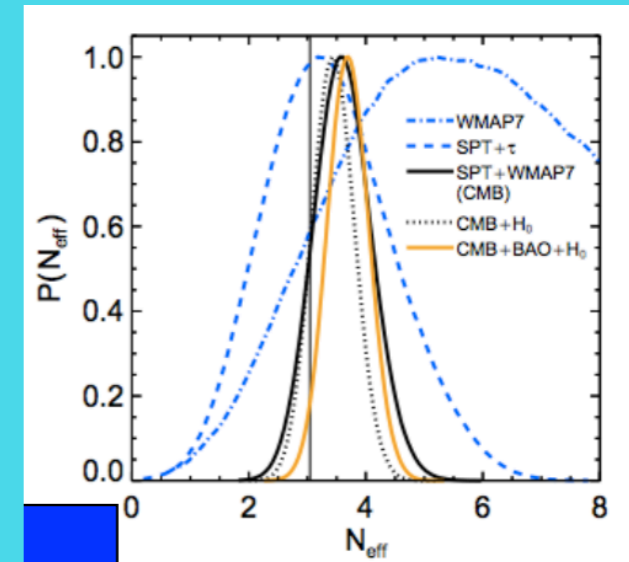
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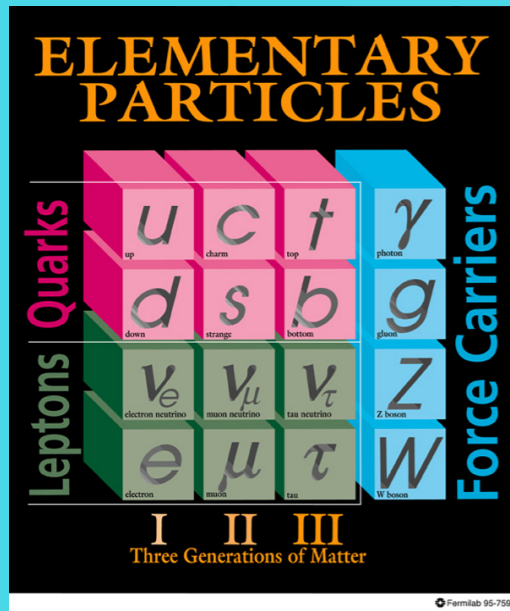


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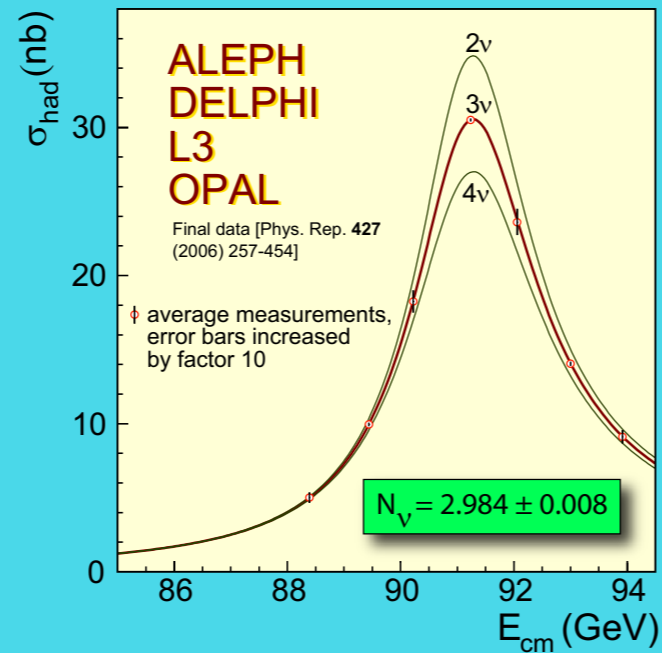
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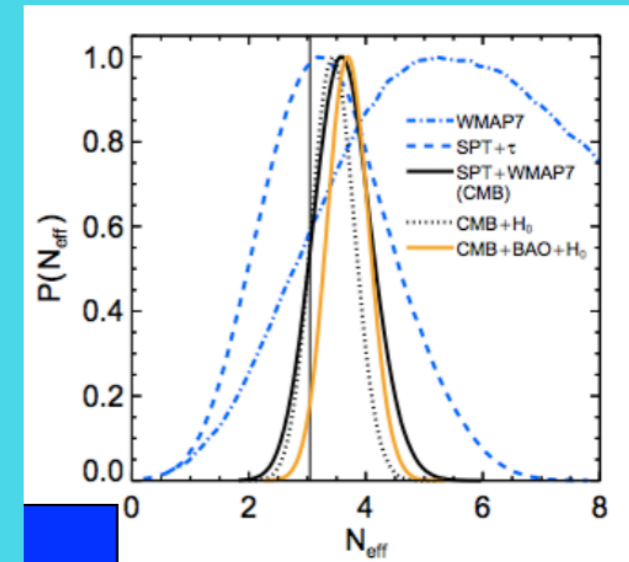
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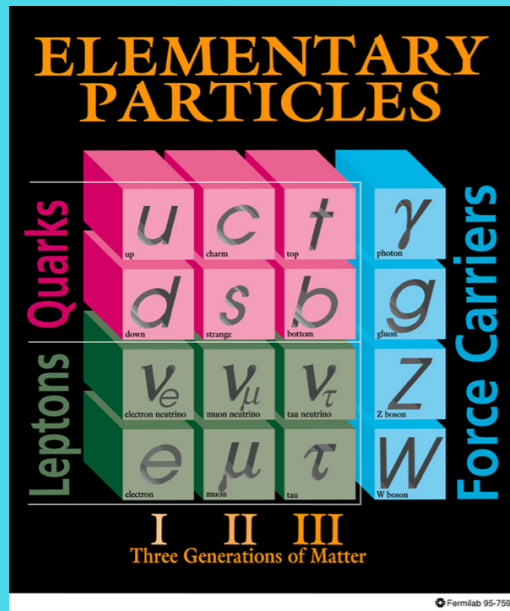


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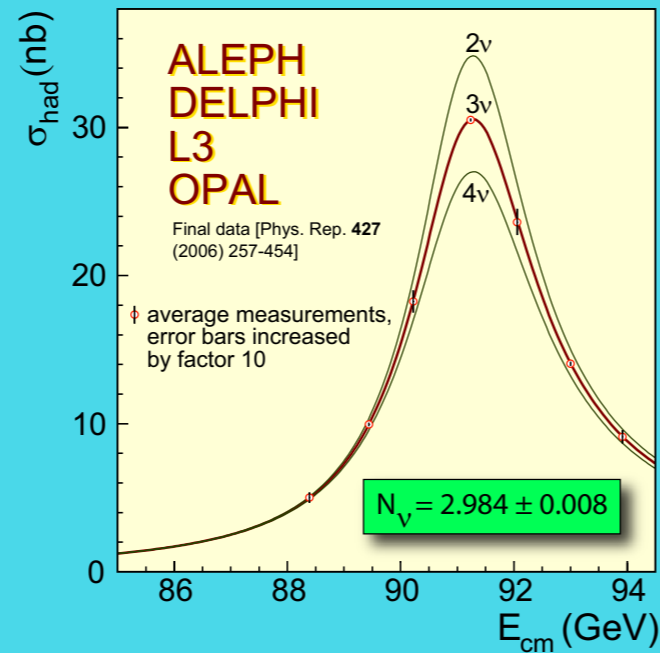
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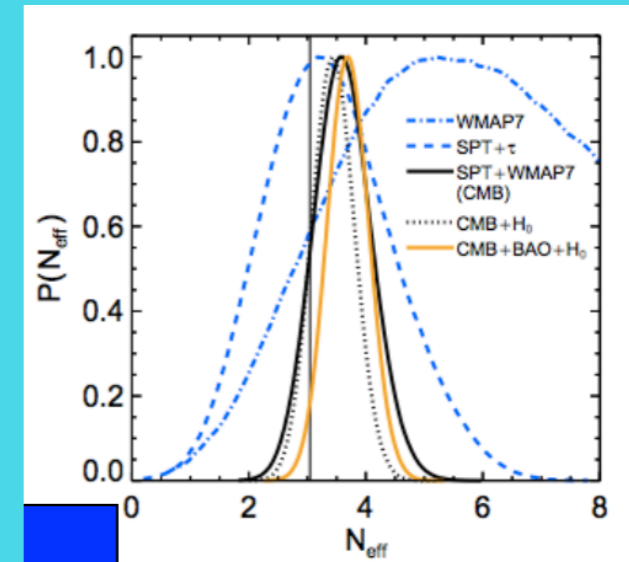
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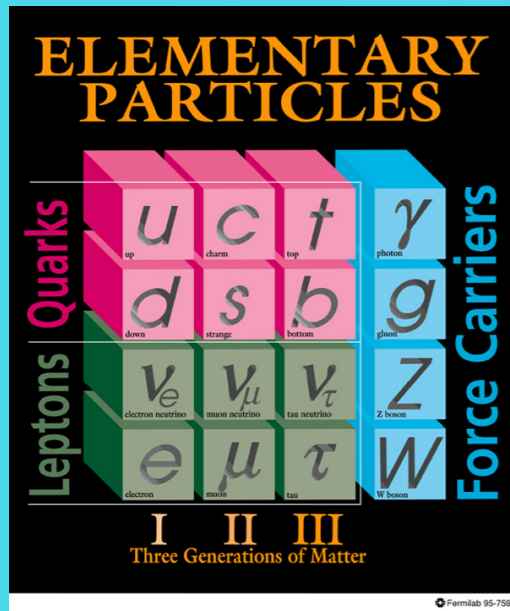


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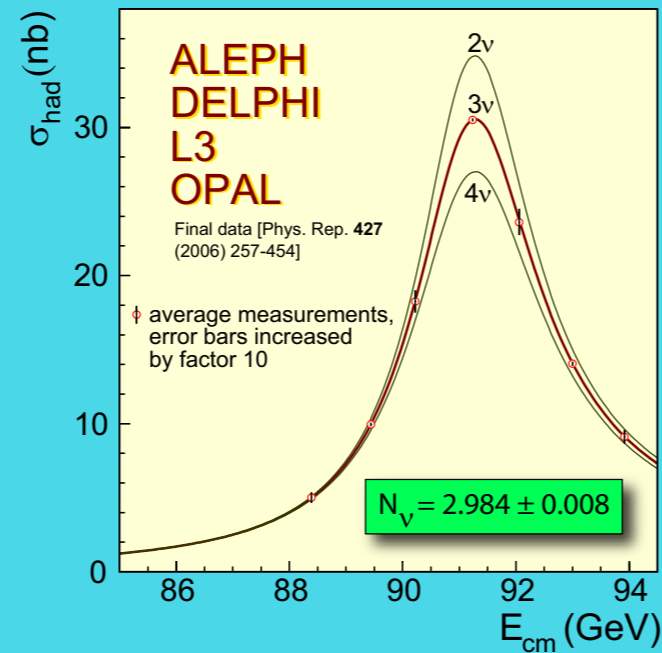
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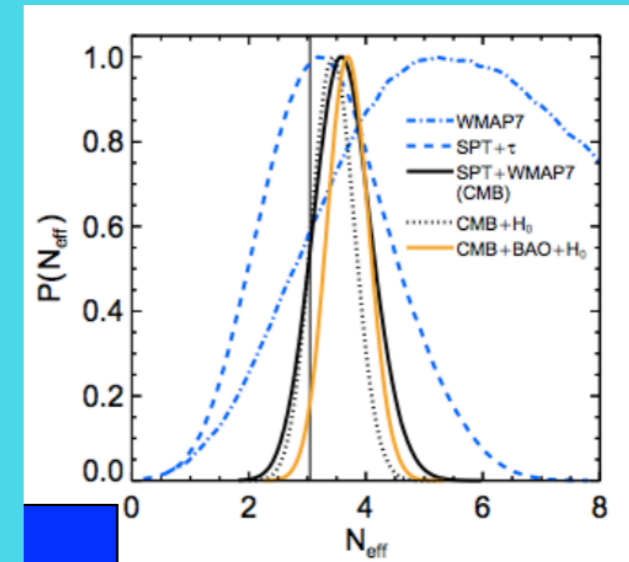
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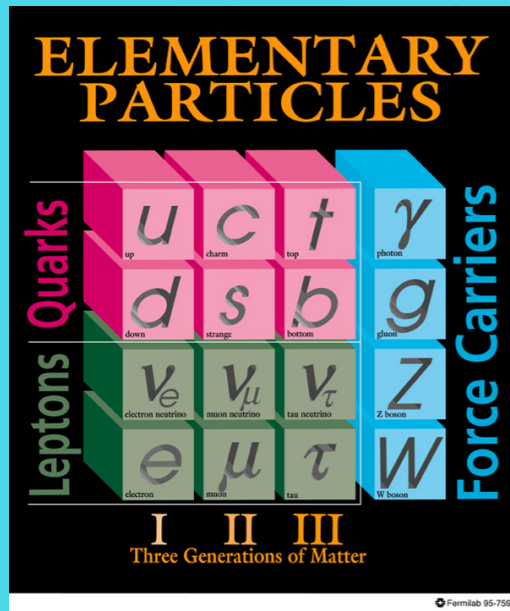
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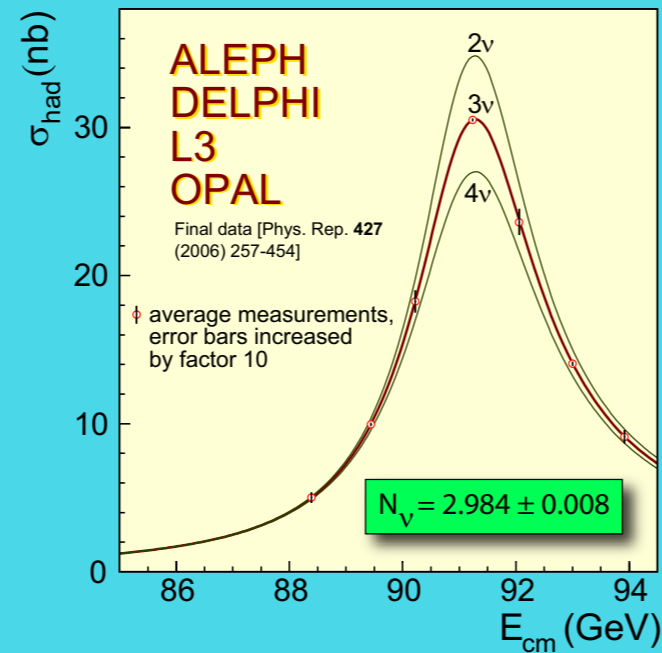
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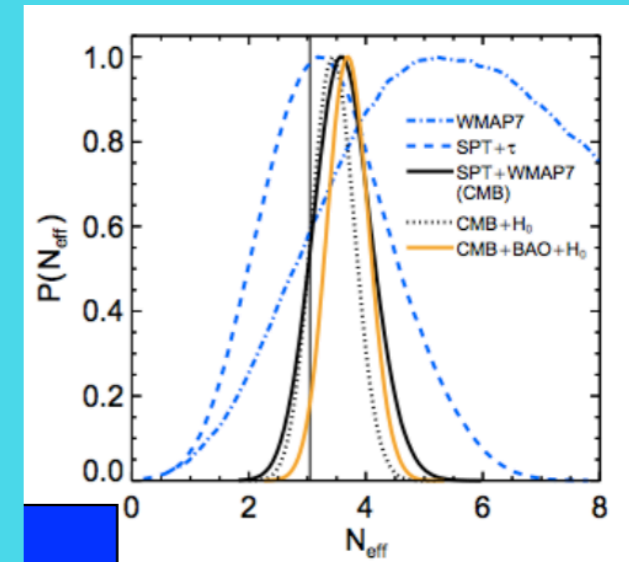
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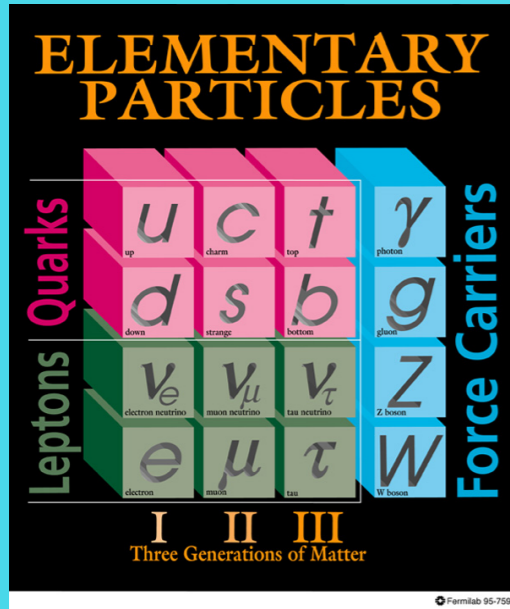
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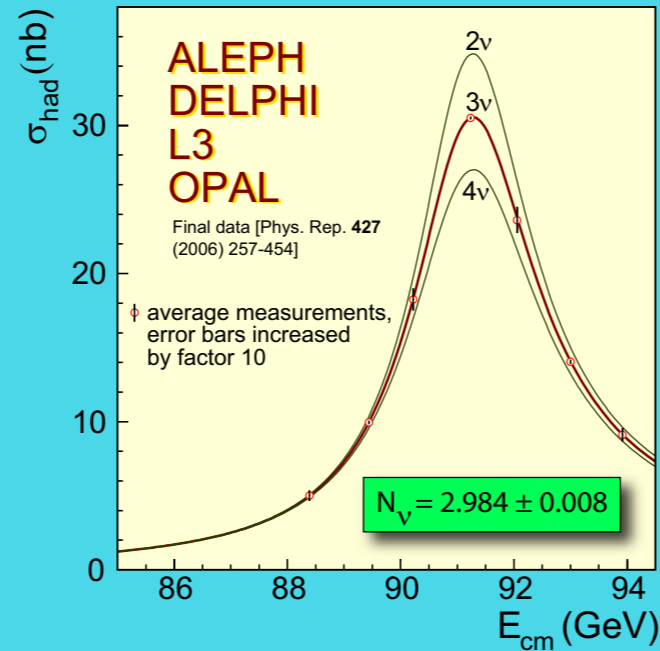
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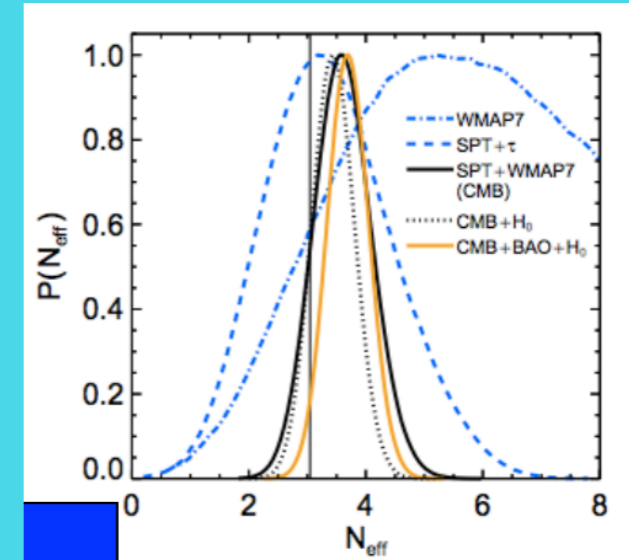
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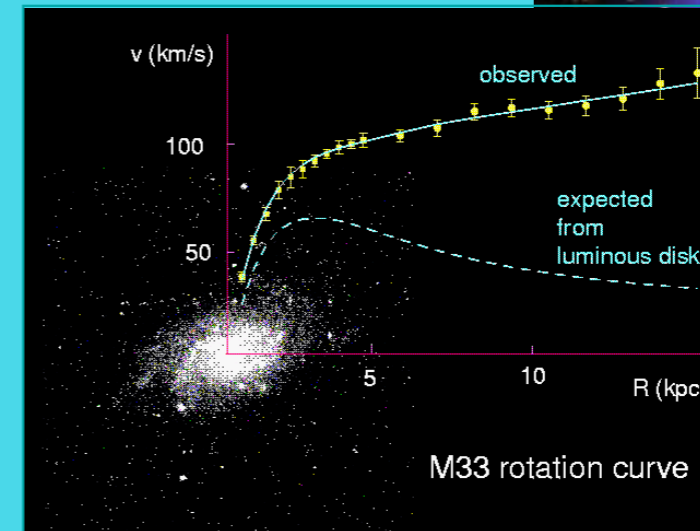
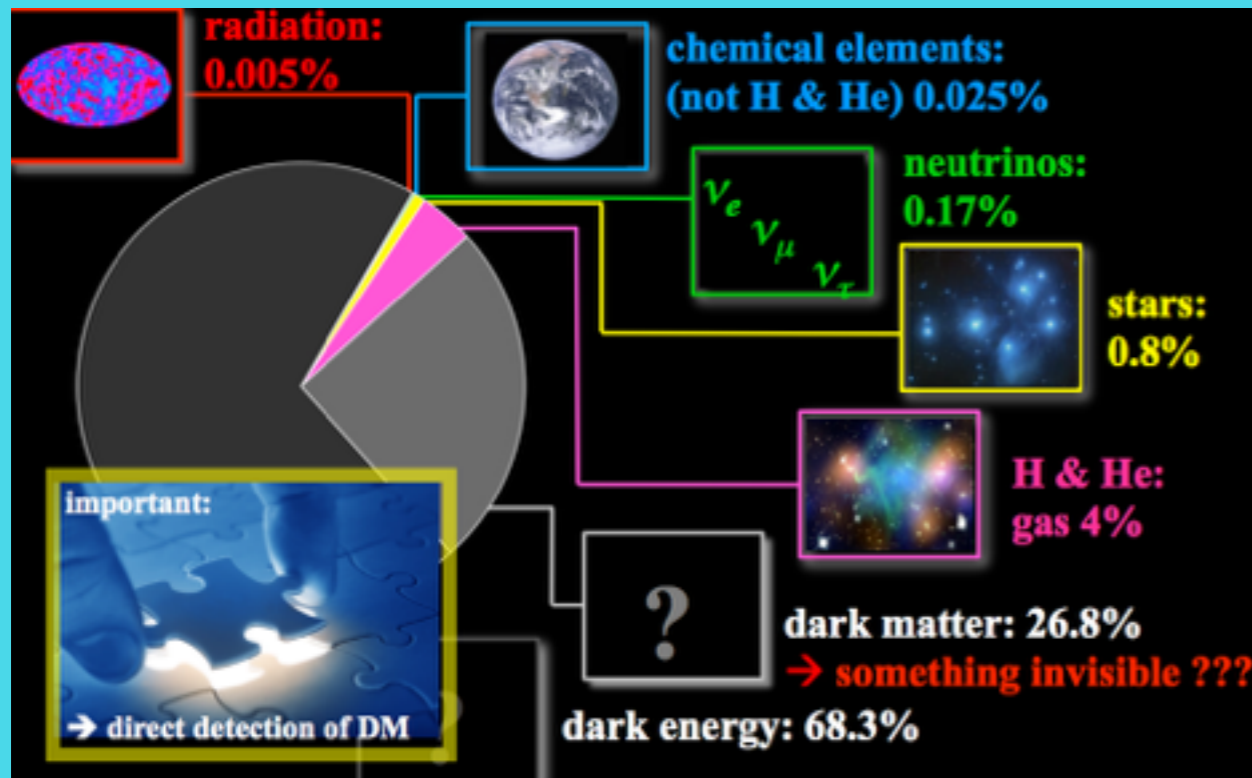
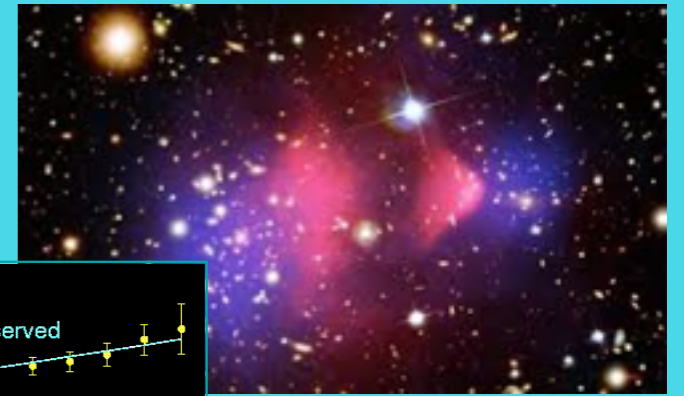
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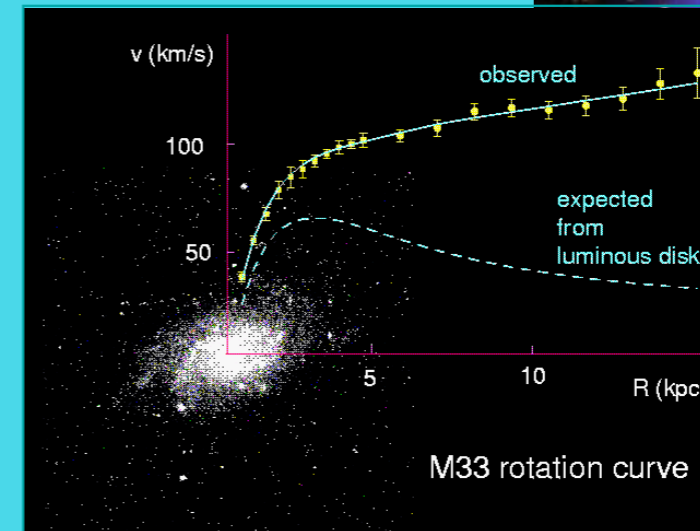
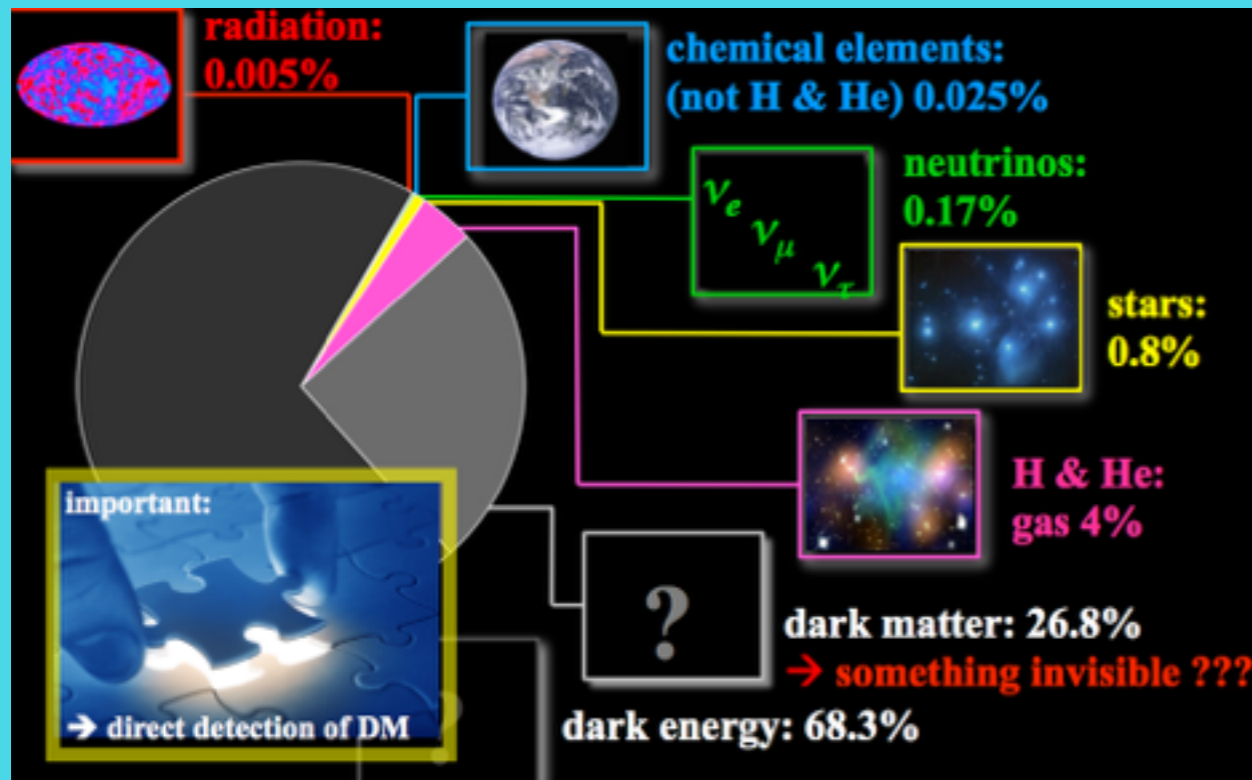
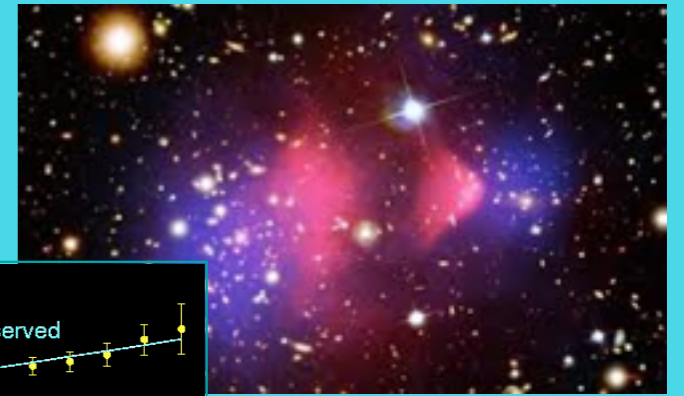
- The fourth generation is excluded also by precision measurement of rare decays

Dark Matter



- rotation curves of stars
- gravitational lensing
- large scale structure of the Universe

Dark Matter

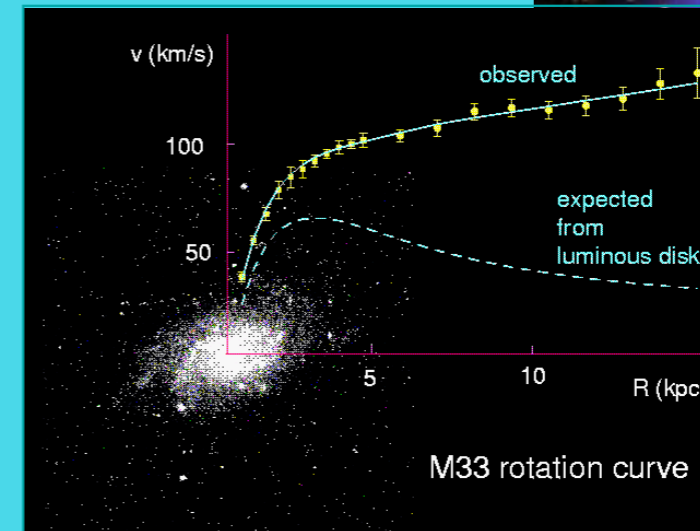
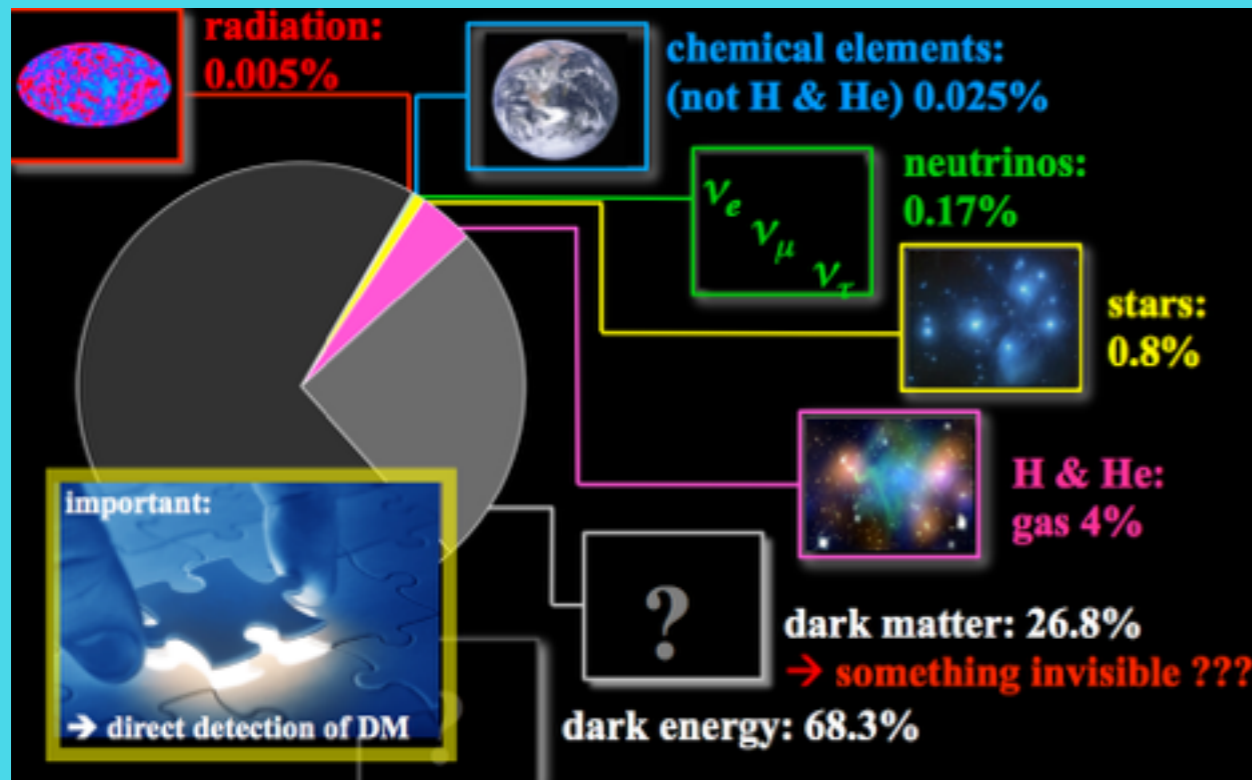
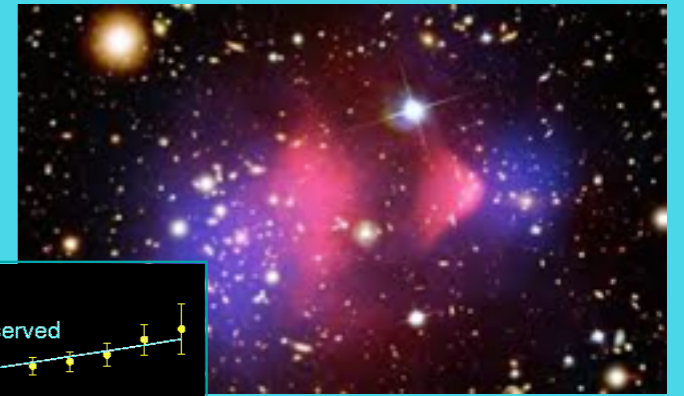


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Dark matter is made of:

- Macro objects- not observed
- New neutral particles

Dark Matter



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WIMP = Weakly Interacting Massive Particle

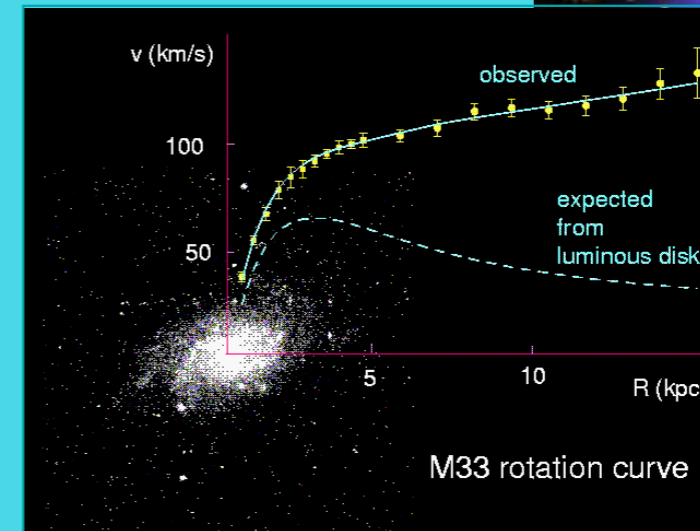
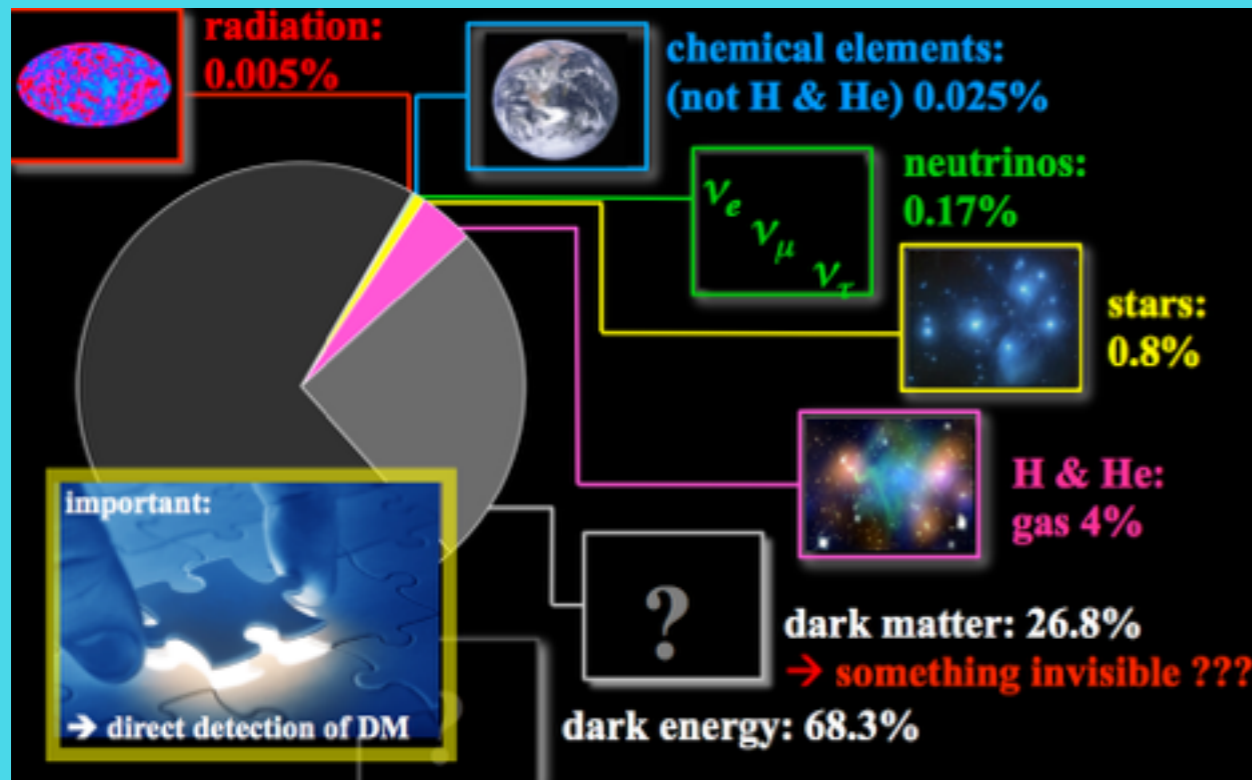
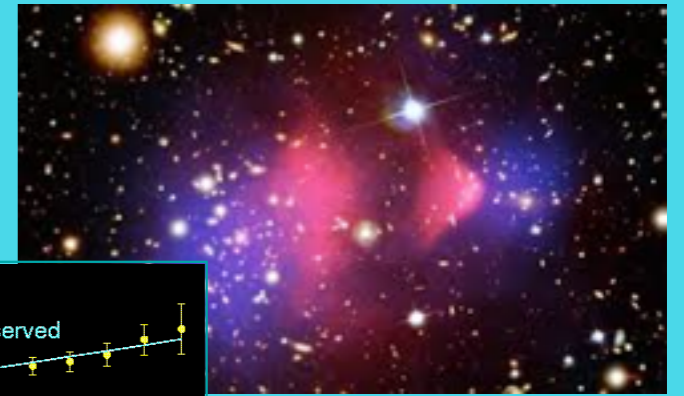
A good argument for new physics at the TeV scale but not fully compelling: DM could well be **axions**

For WIMPs in thermal equilibrium after inflation

$$\langle \sigma_{\text{ann}} v \rangle \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$$

EW x-section for particle with $M \sim 10^{2-3} \text{ GeV}$

Dark Matter

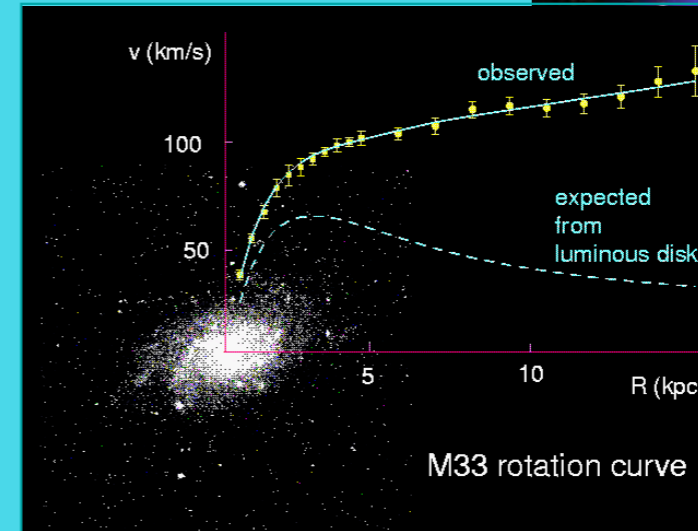
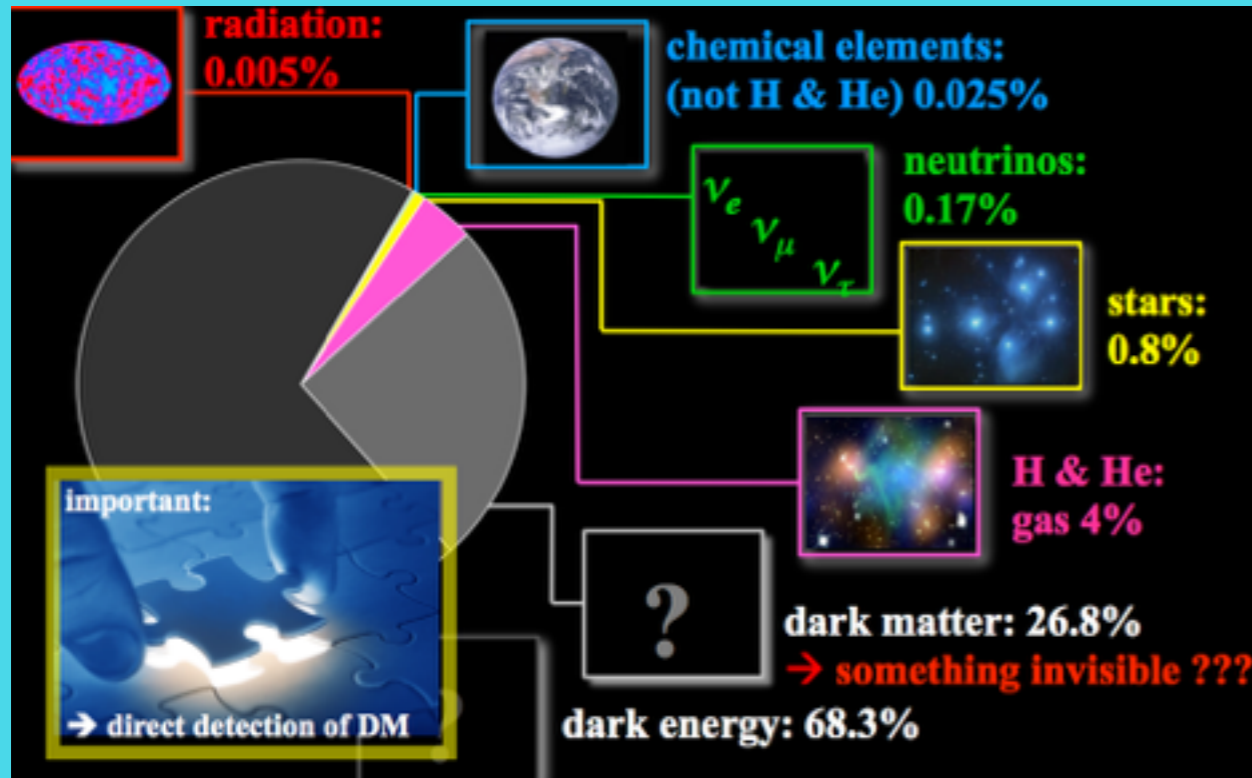
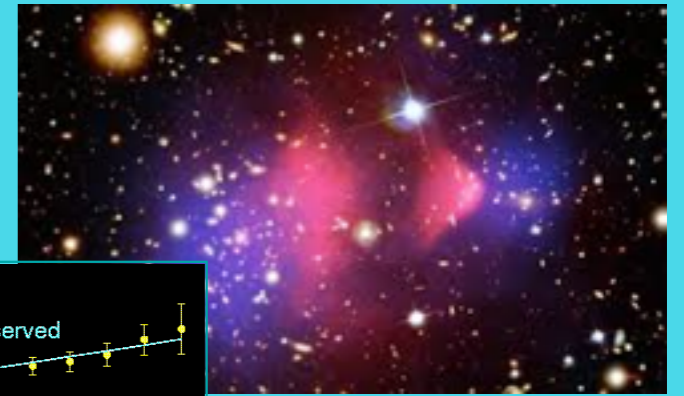


- rotation curves of stars
- gravitational lensing
- large scale structure of the Universe

Dark matter is made of:

- Macro objects- not observed
- New neutral particles

Dark Matter

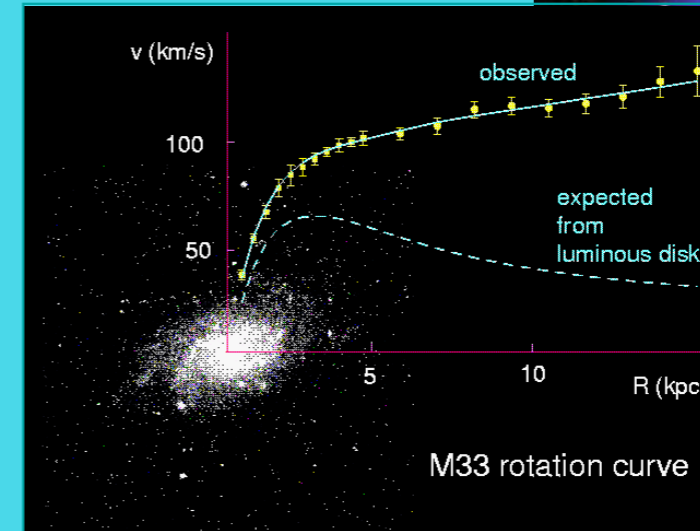
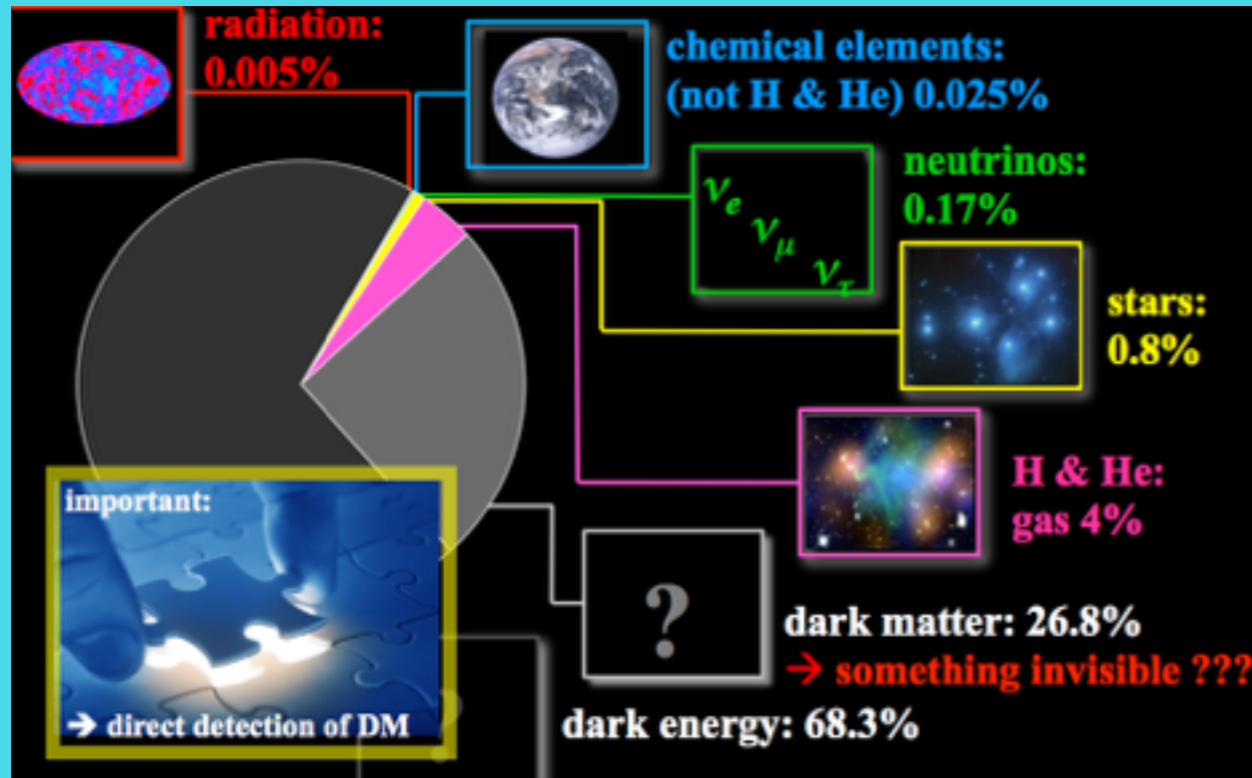
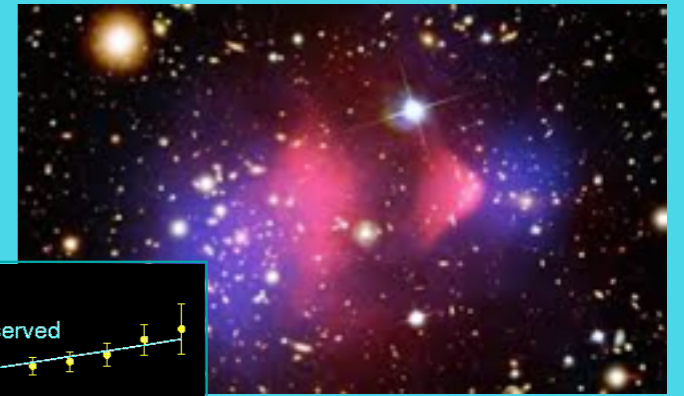


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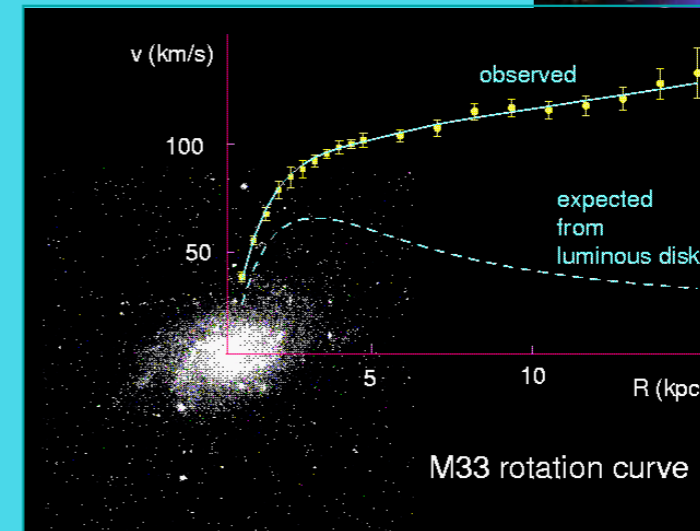
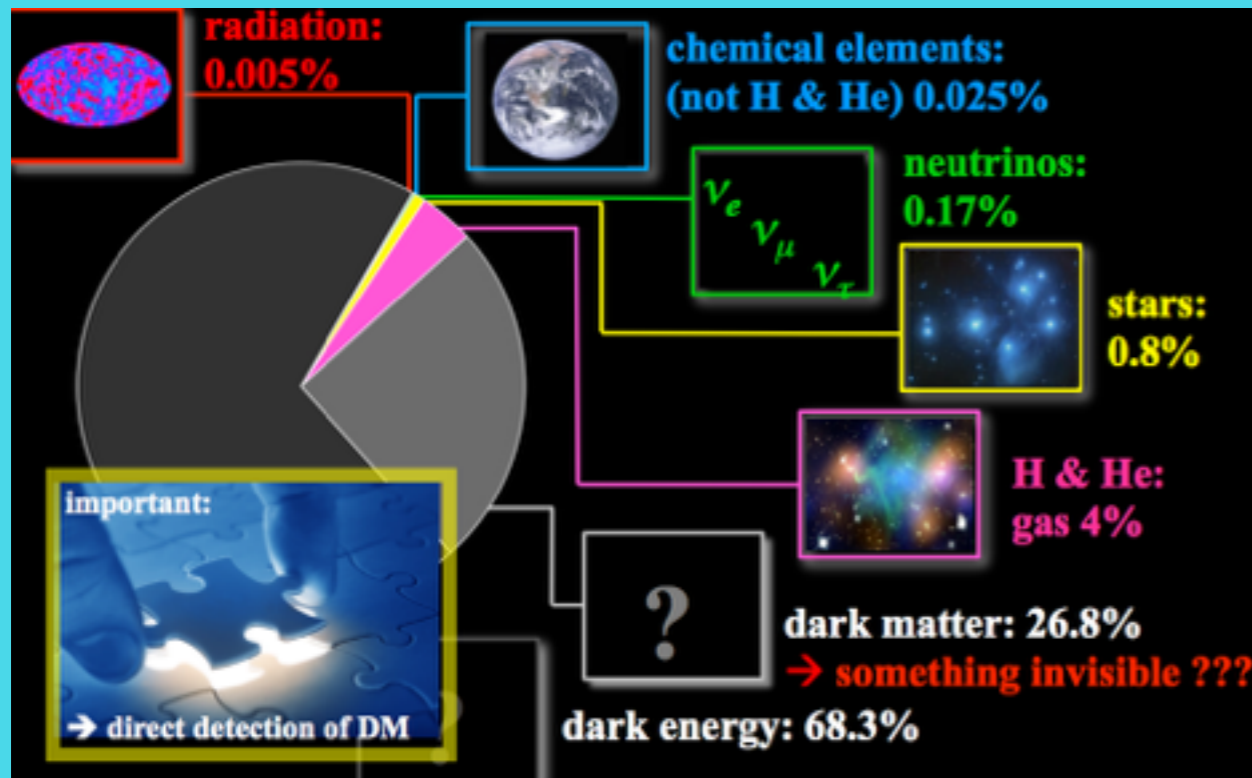
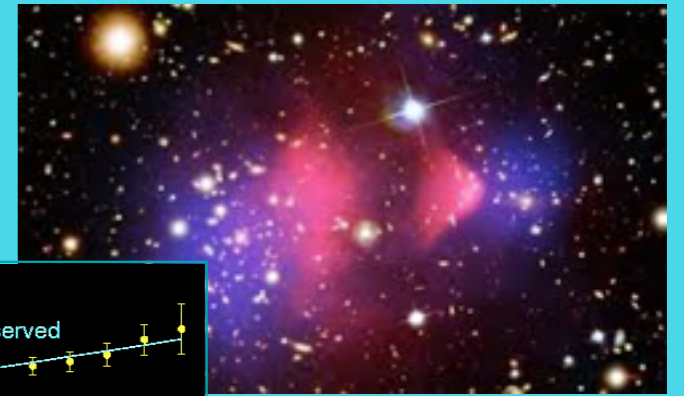


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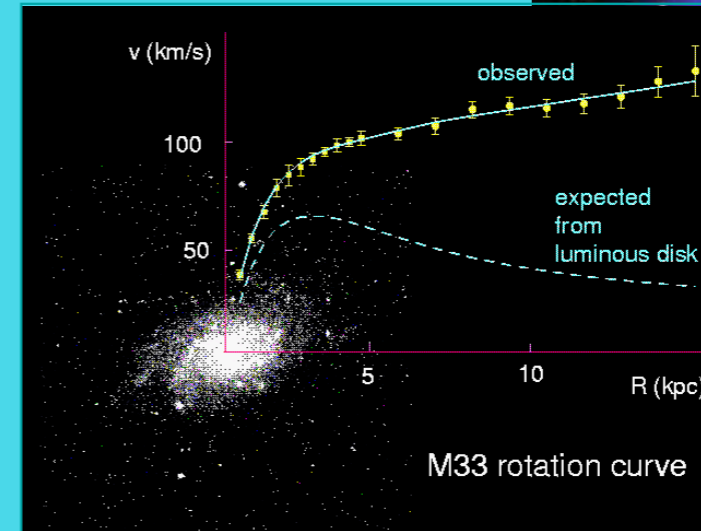
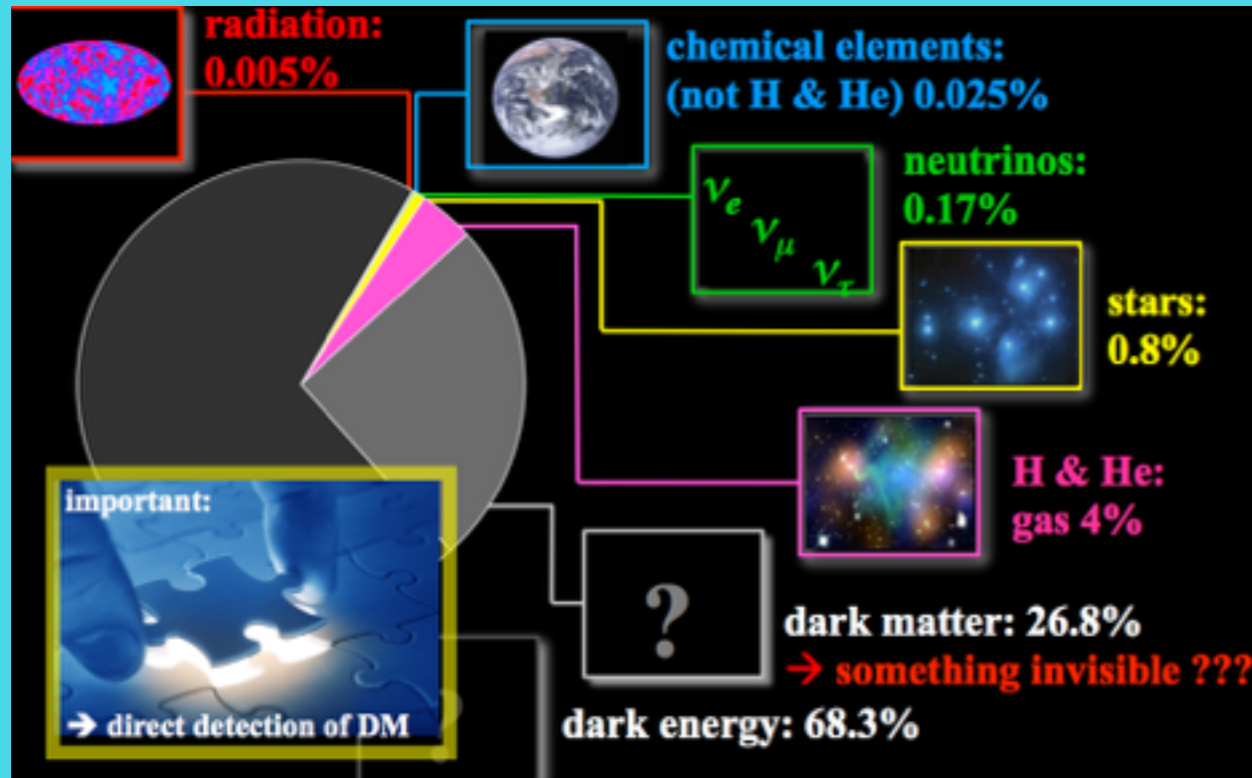
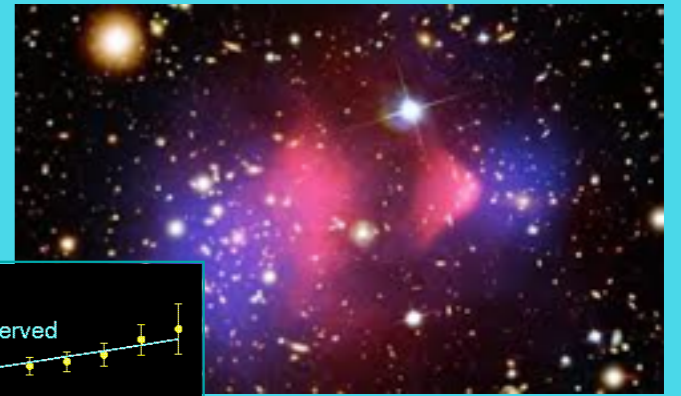


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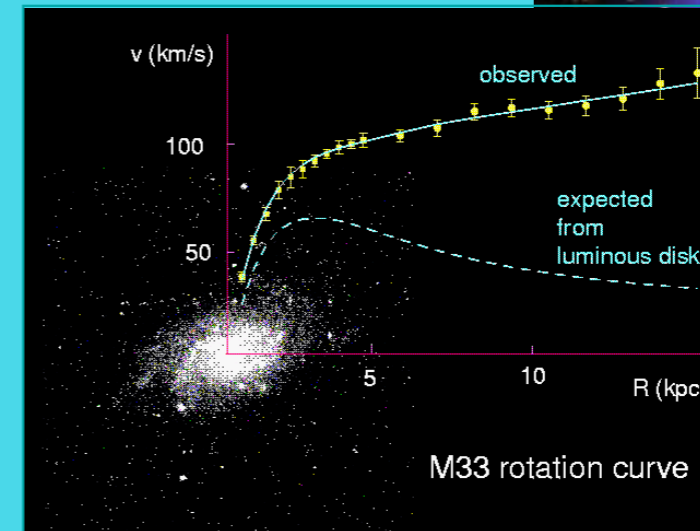
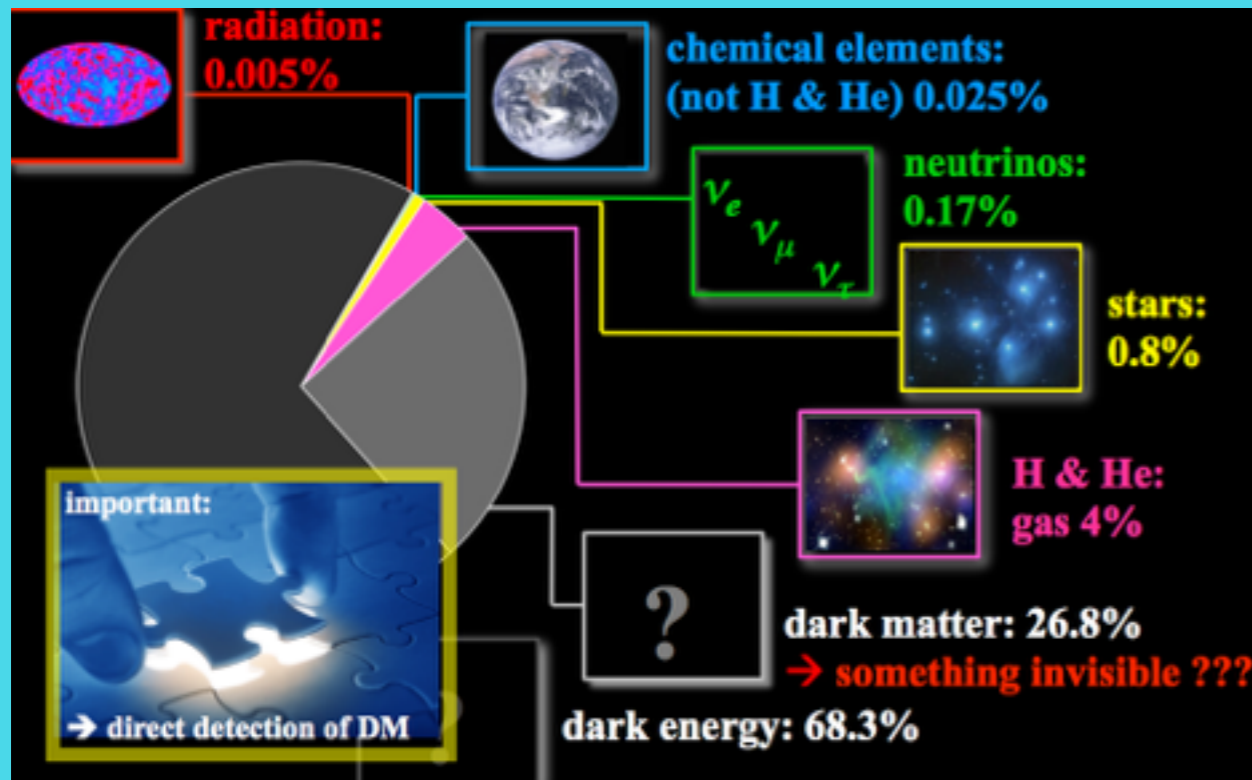
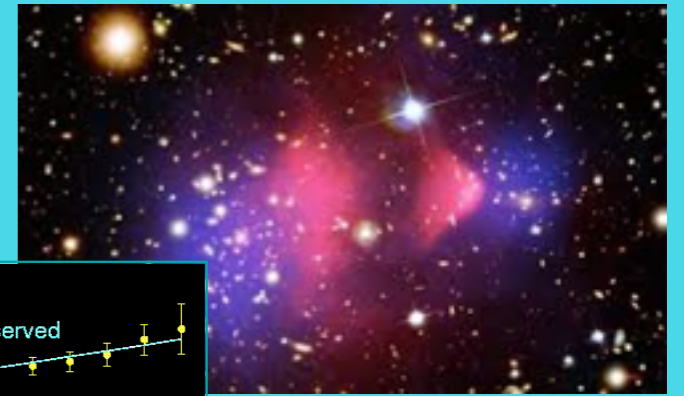


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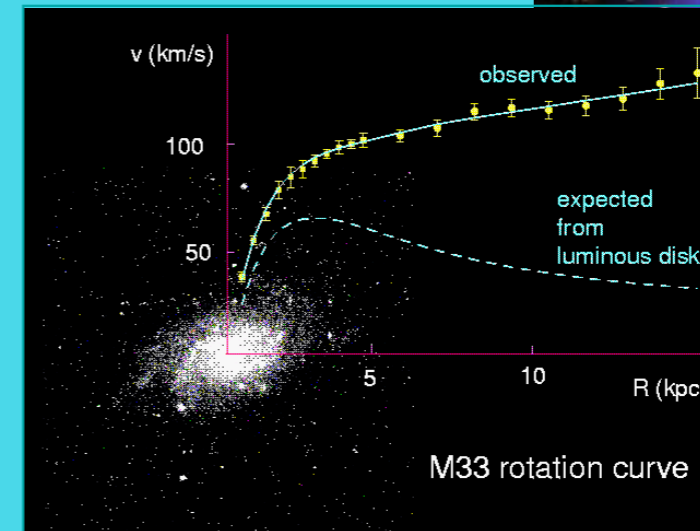
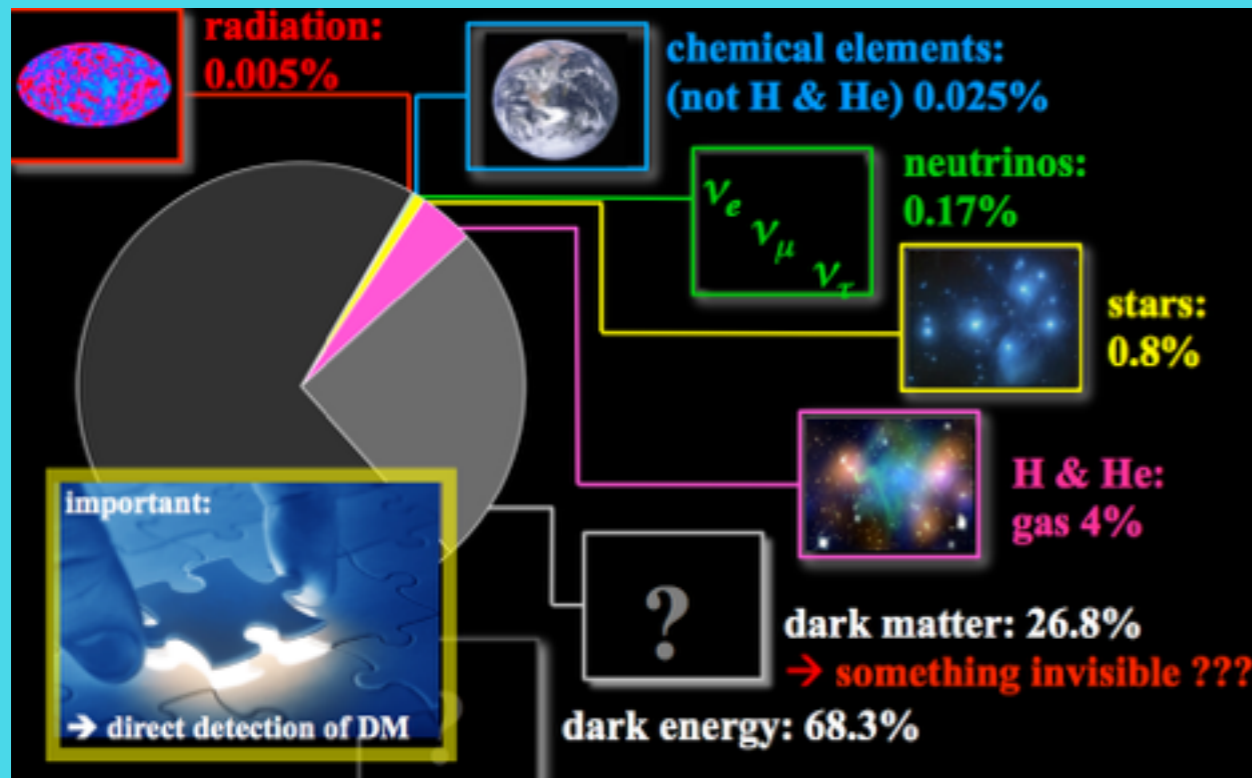
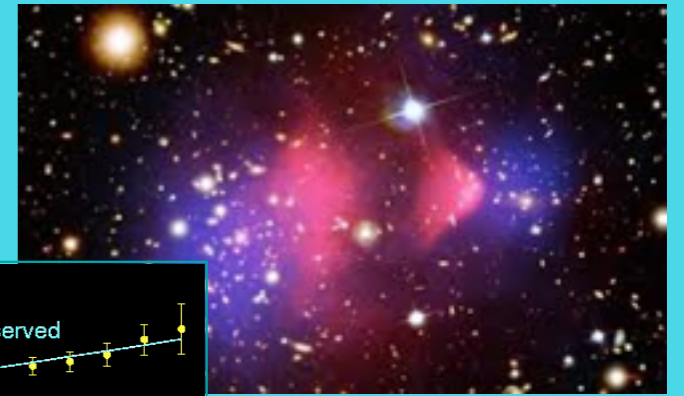


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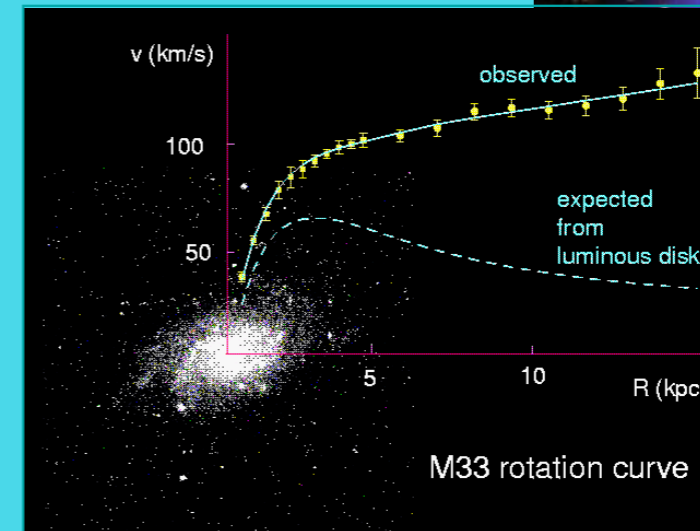
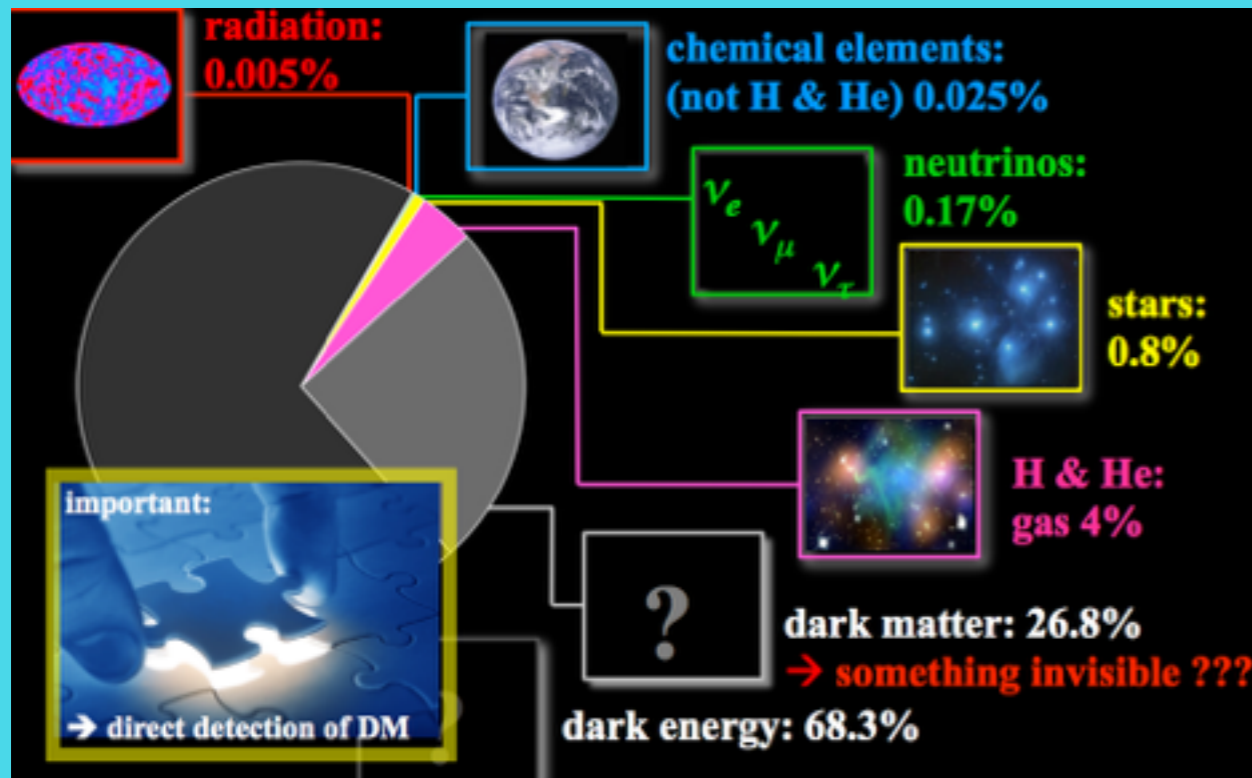
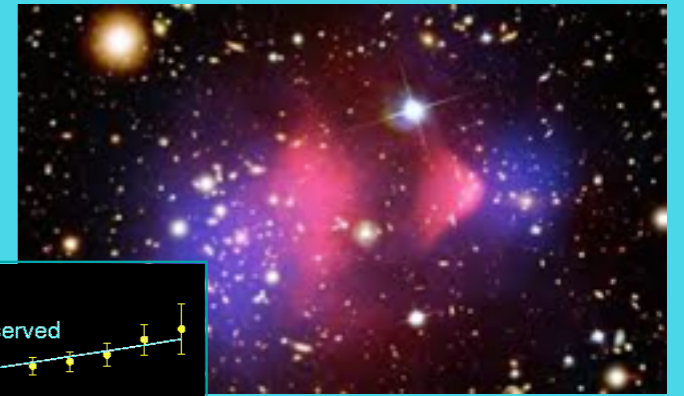


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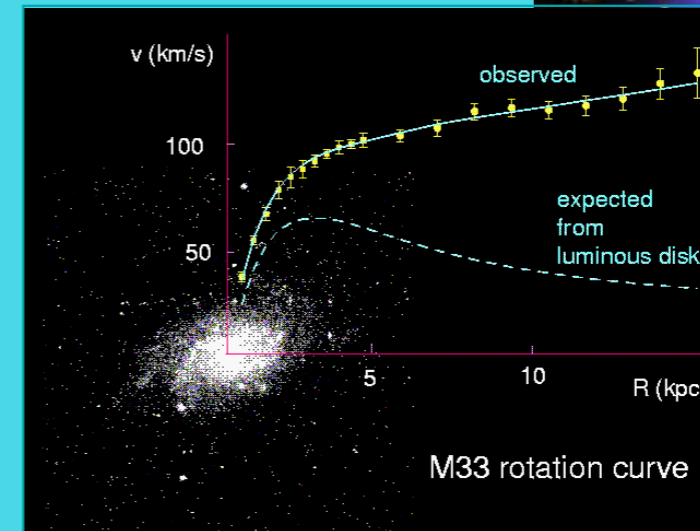
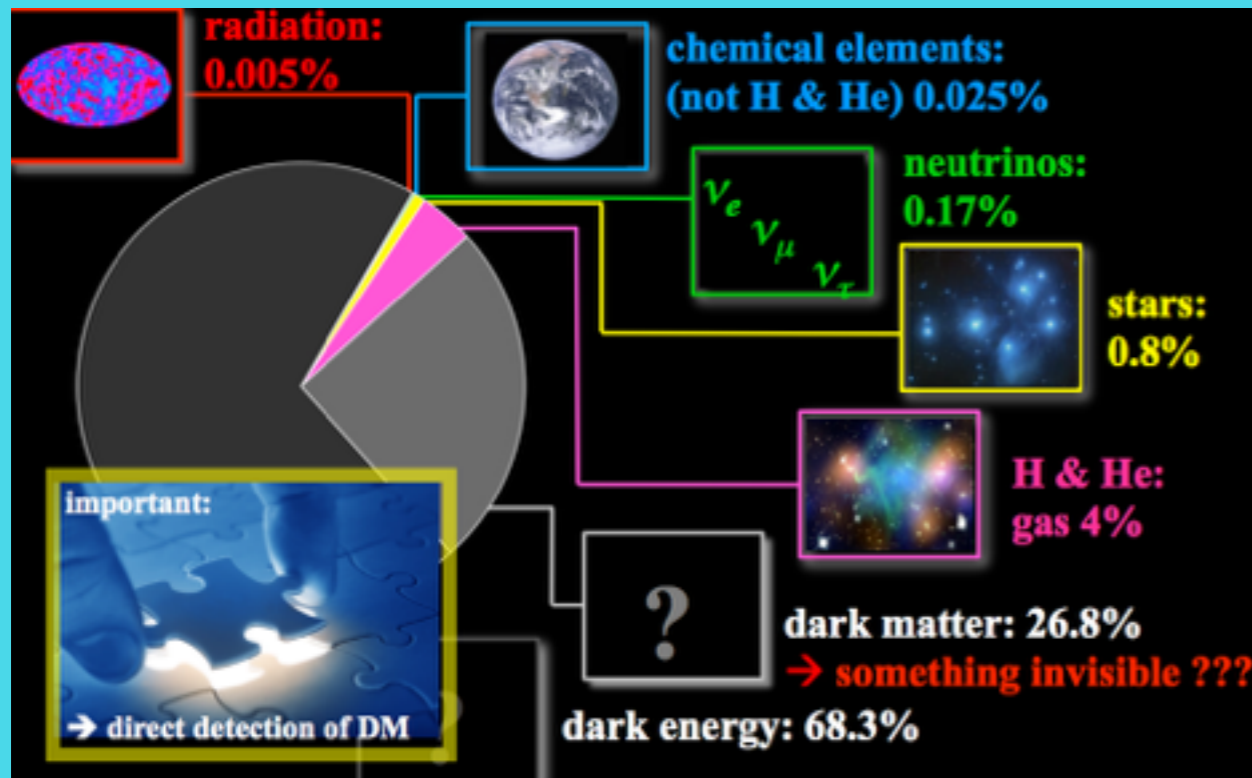
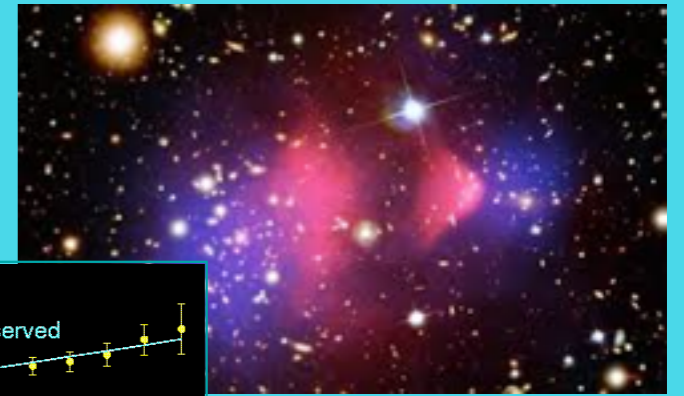


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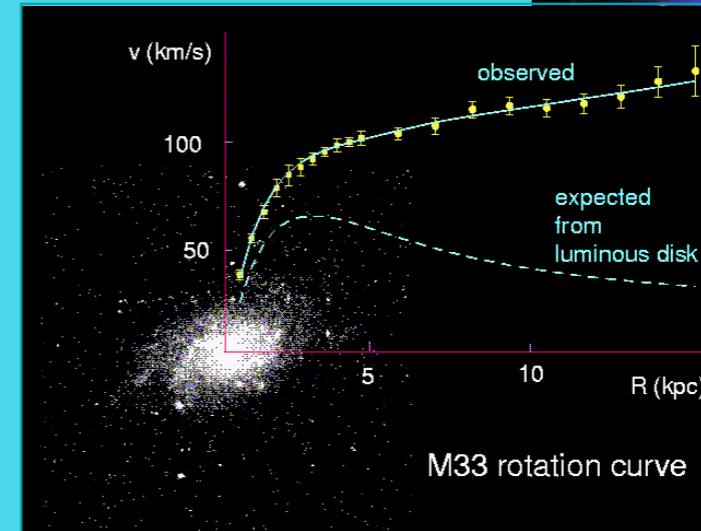
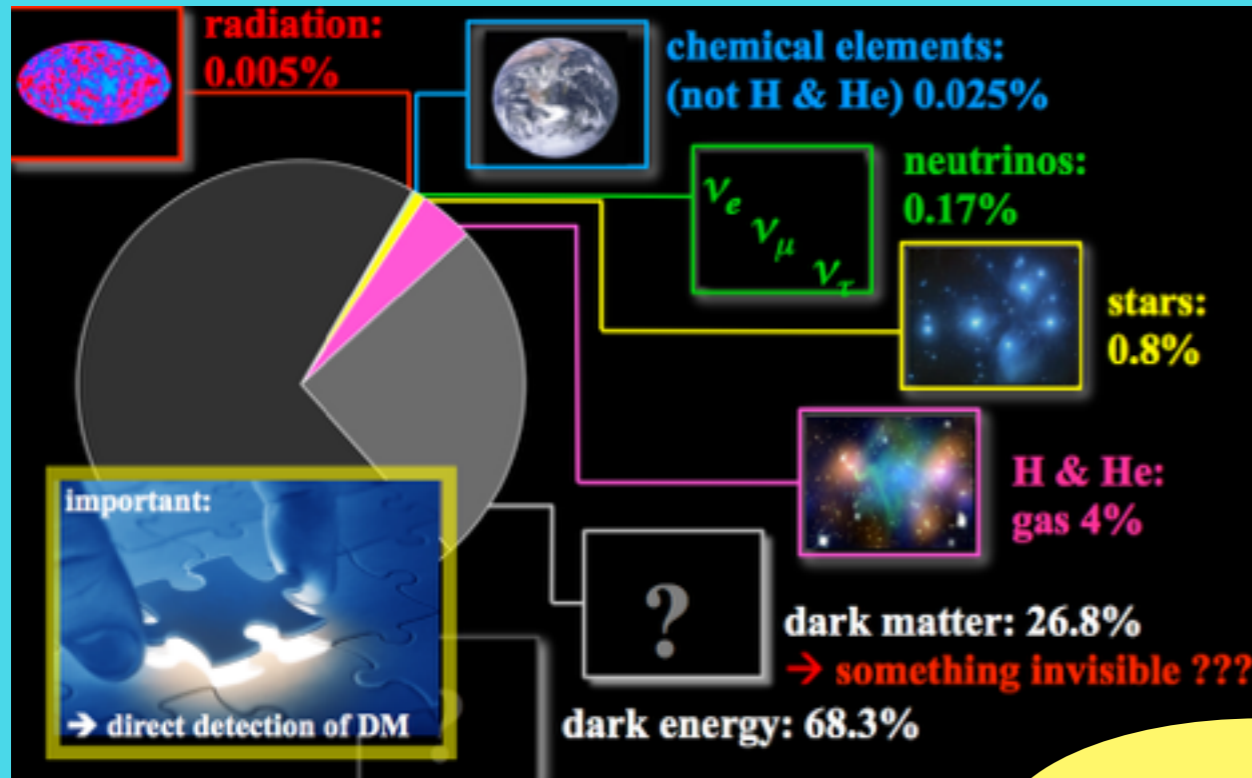
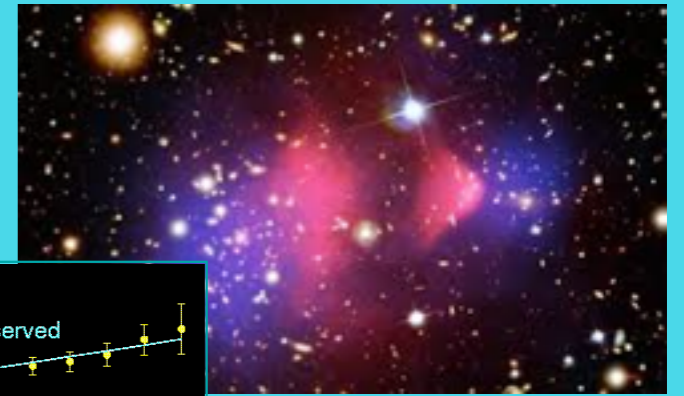
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Dark Matter



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The only candidate in the SM

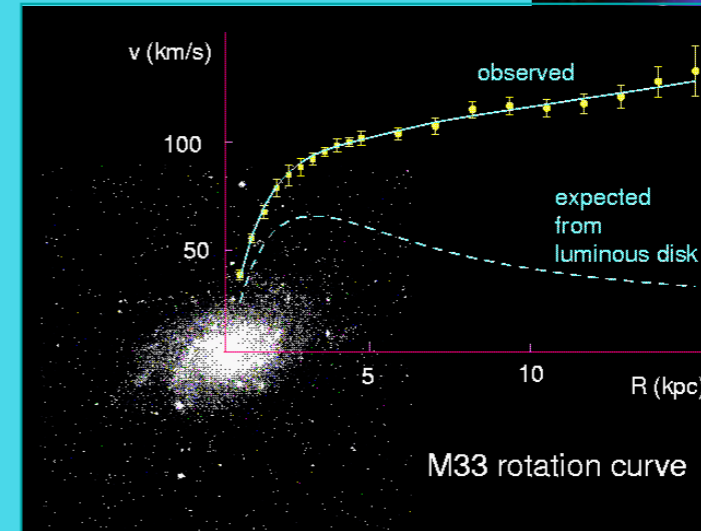
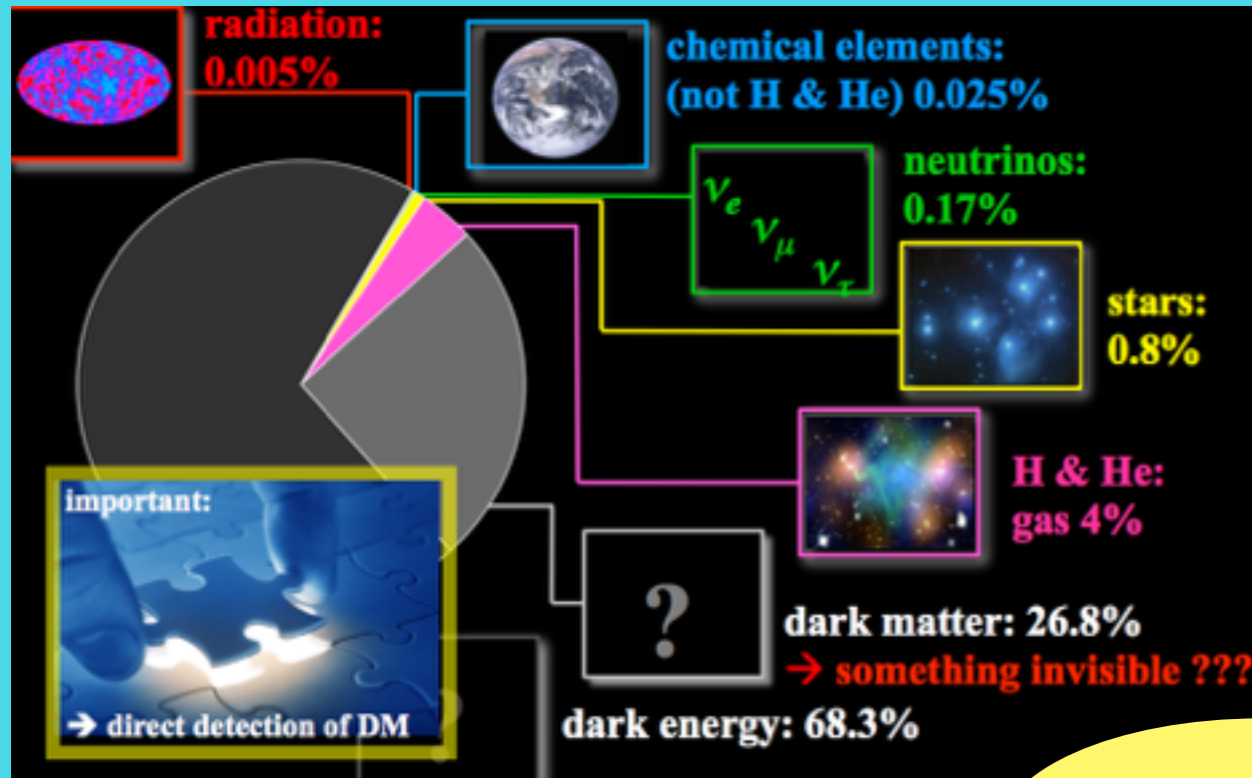
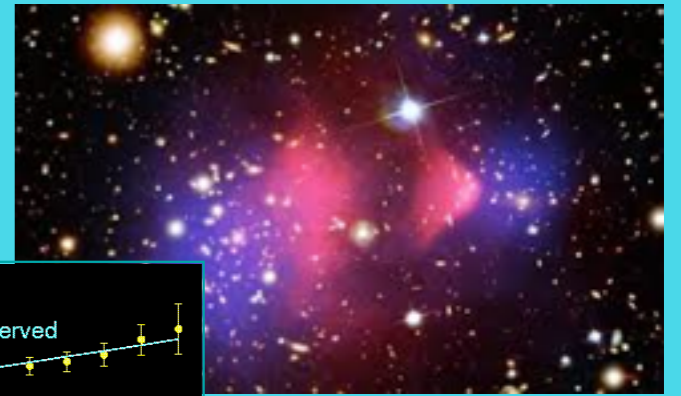
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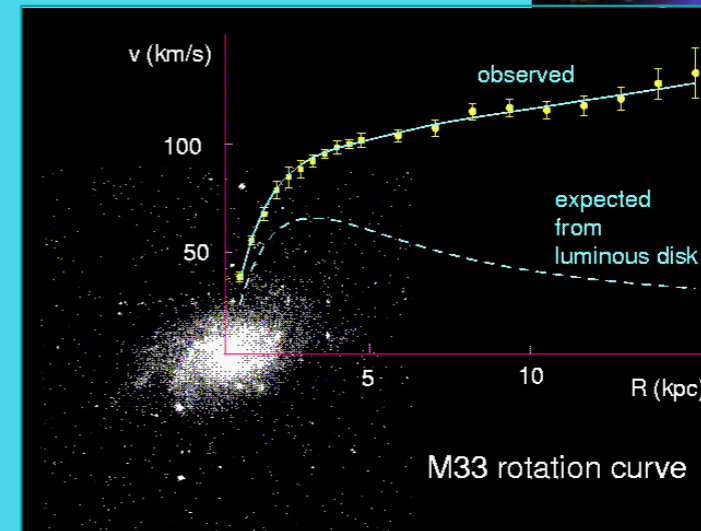
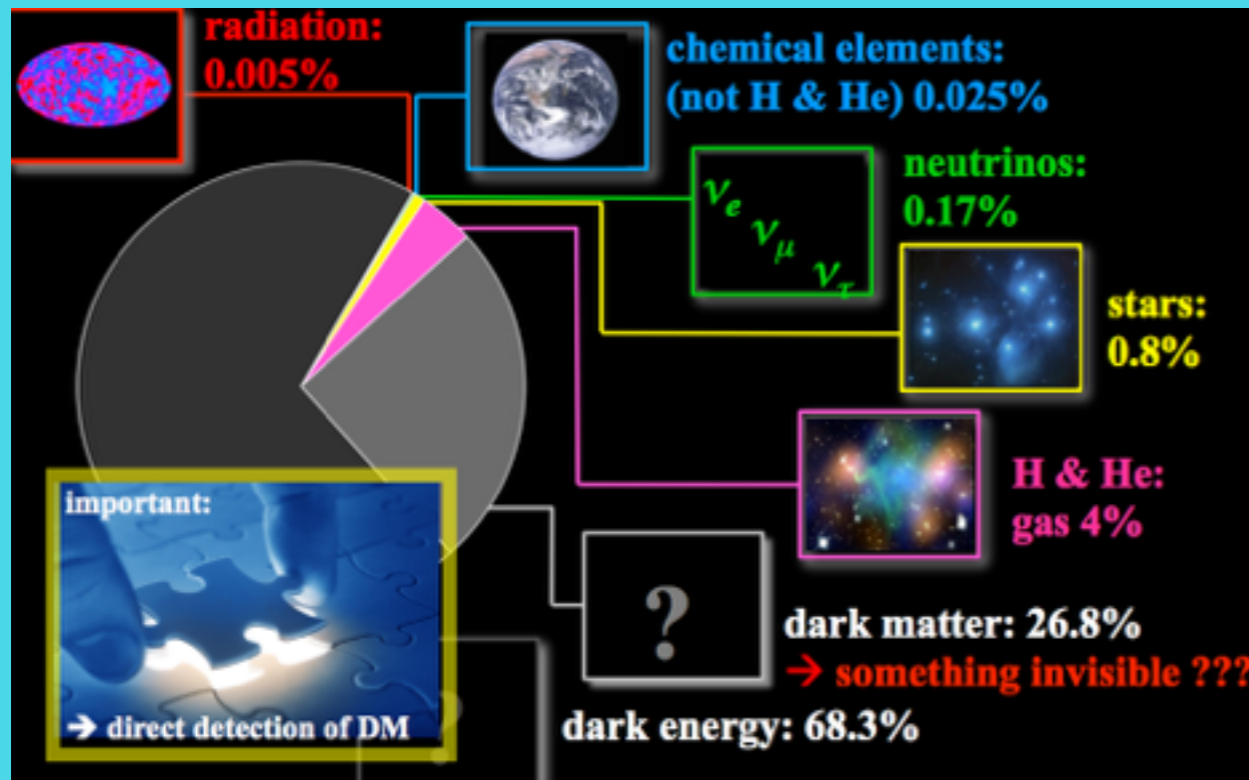
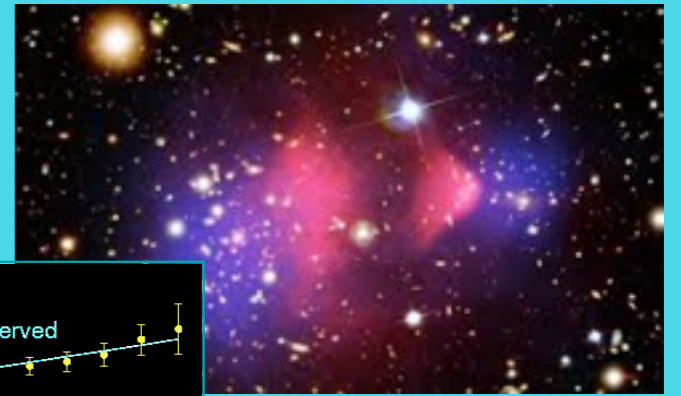
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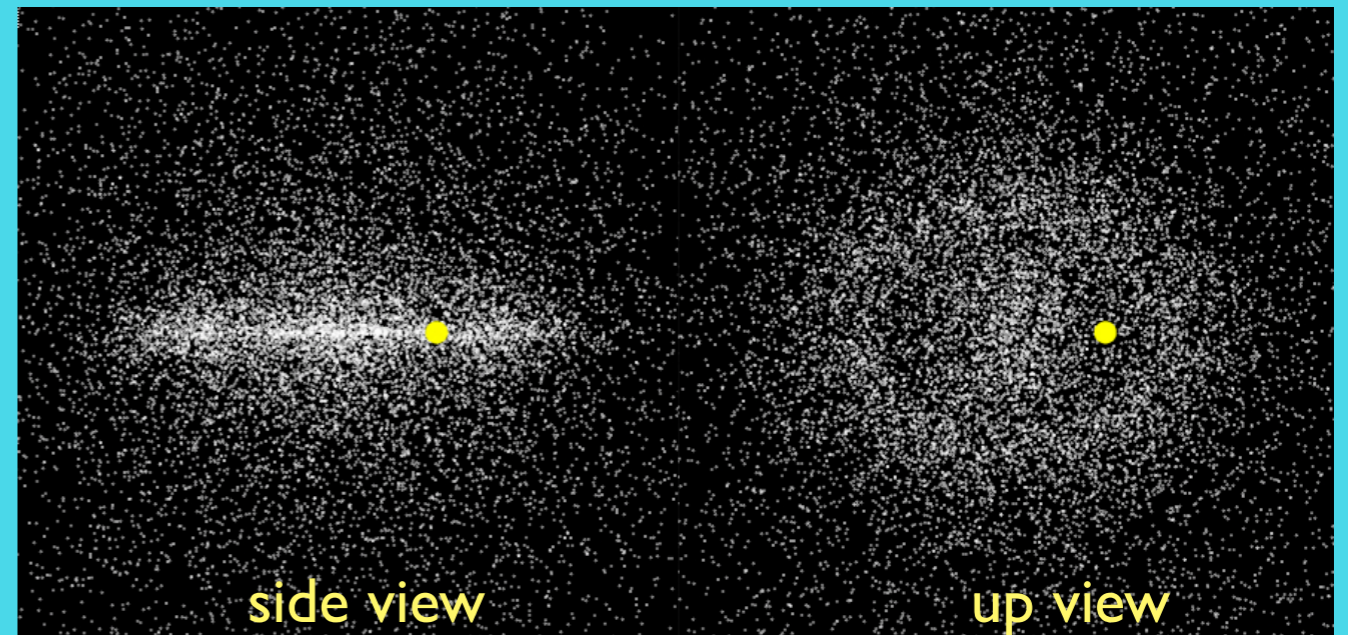


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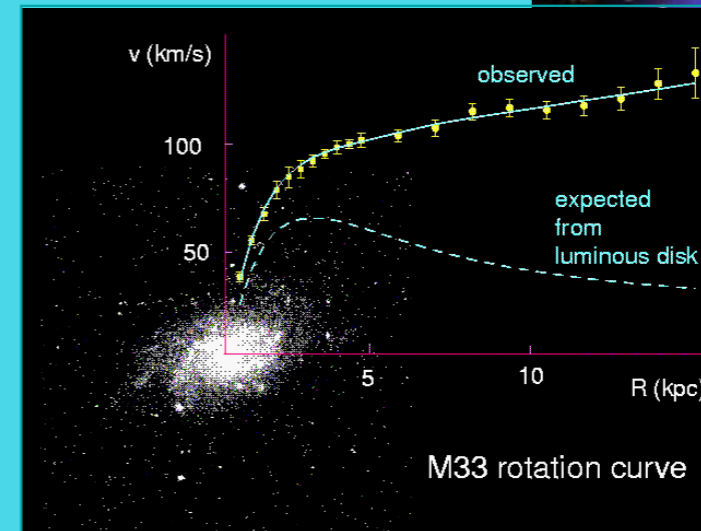
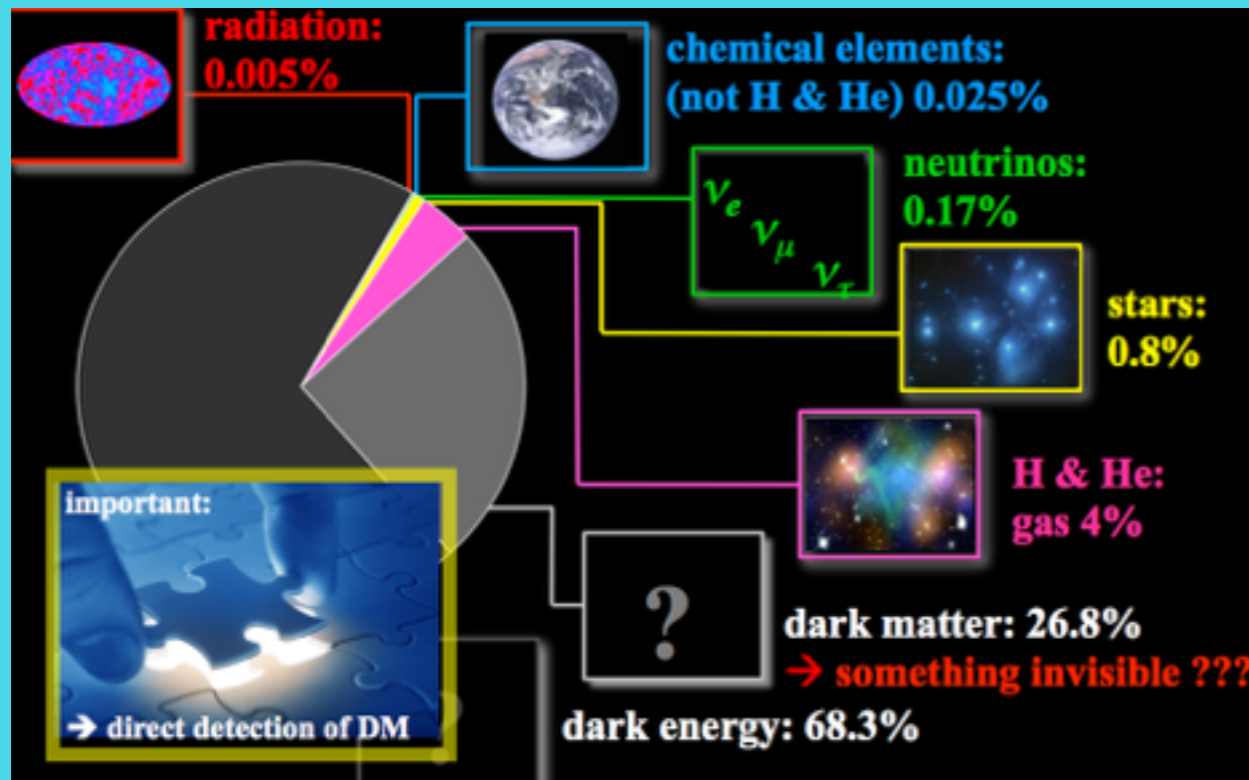
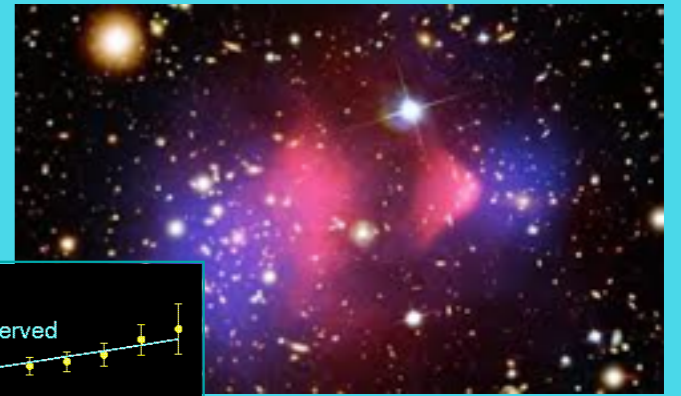
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The structure of the DM halo in Milky Way

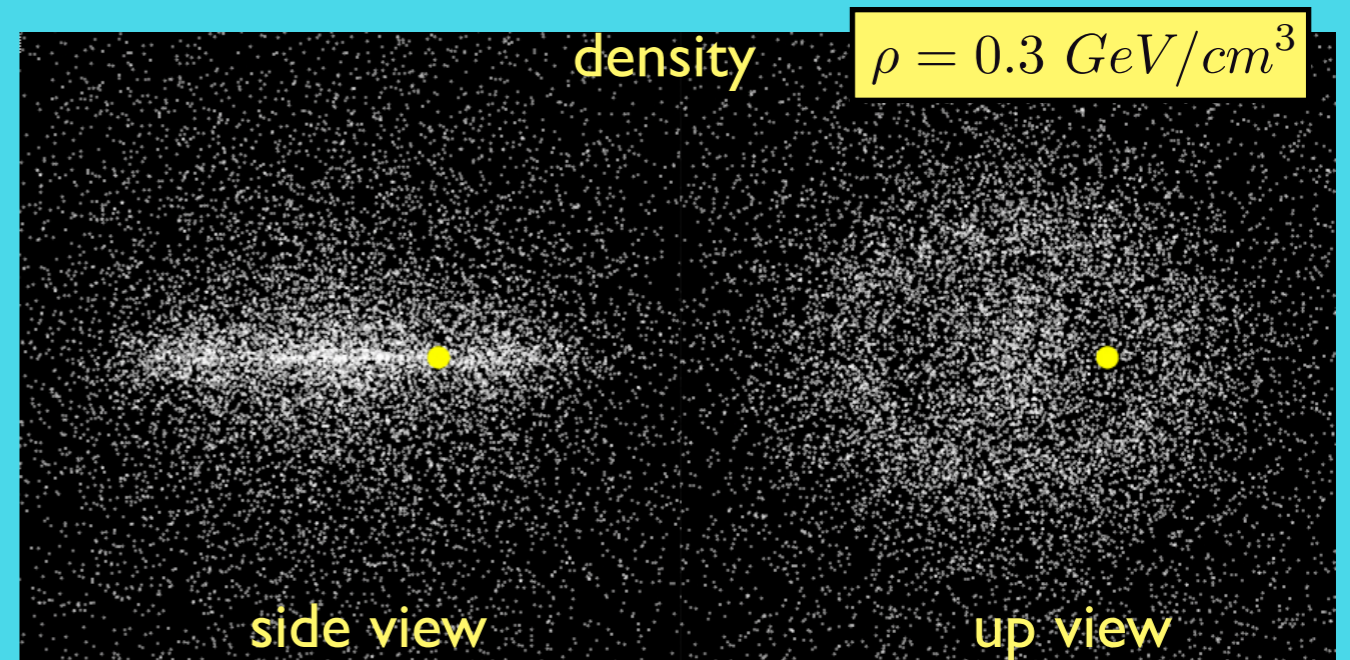
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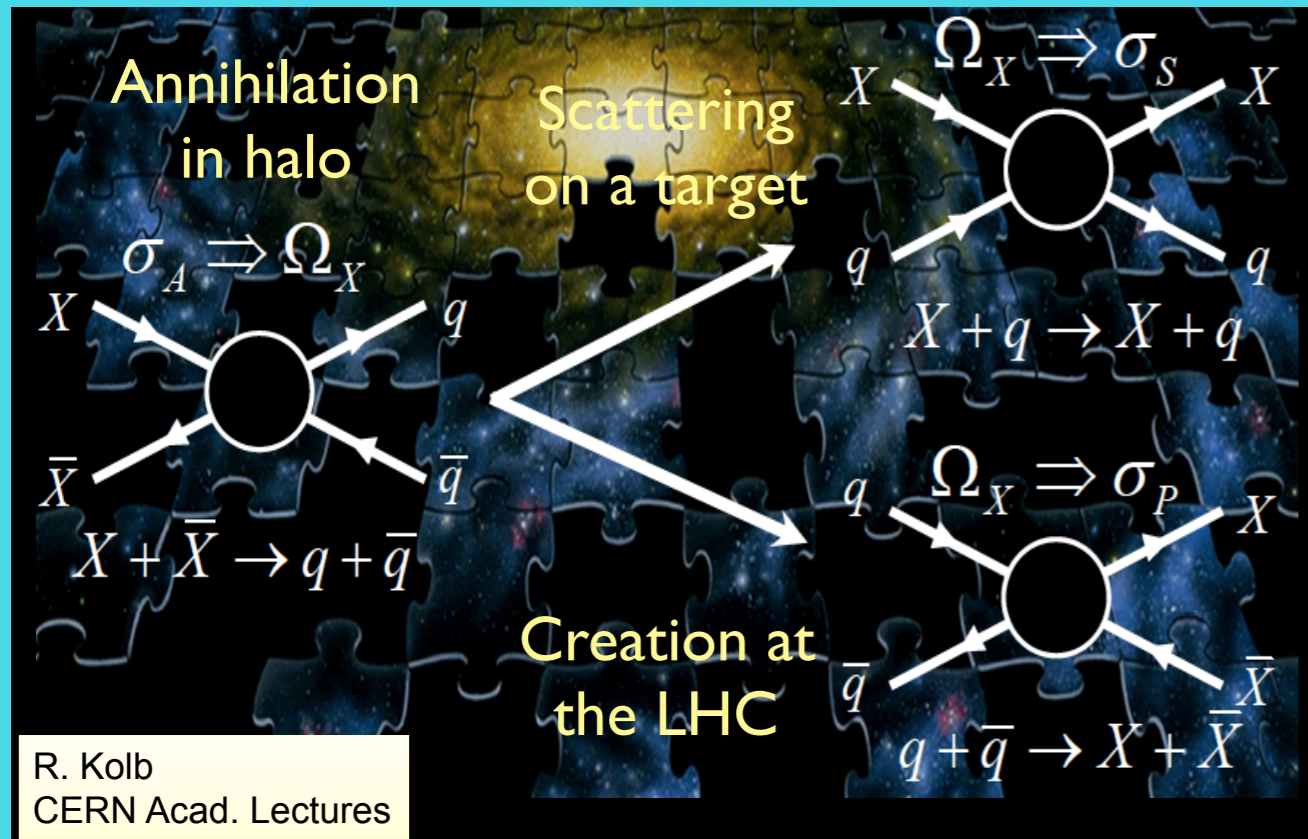
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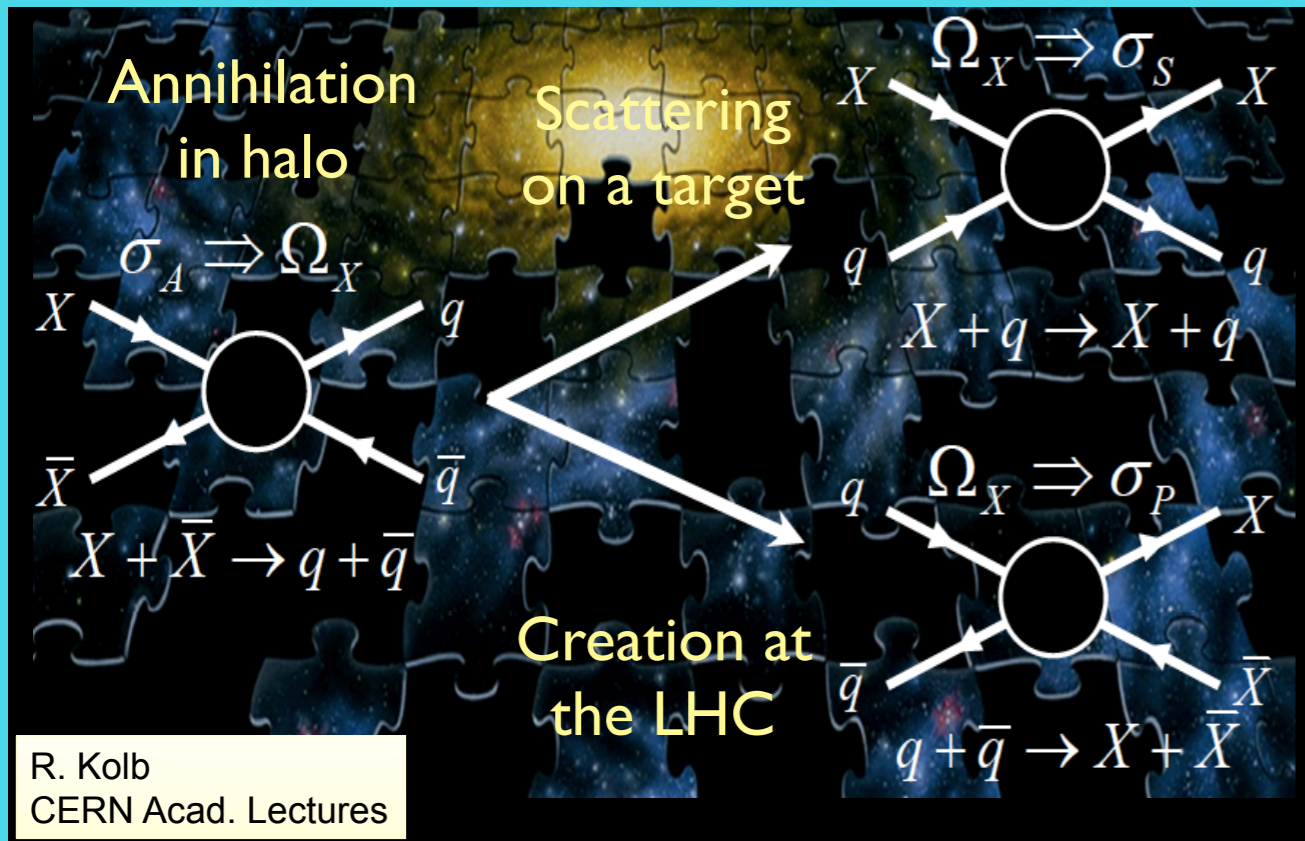


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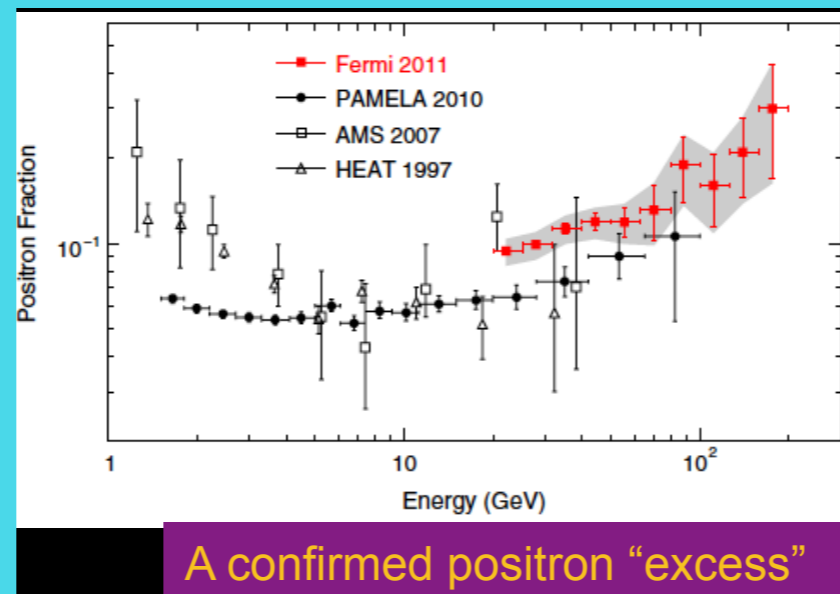
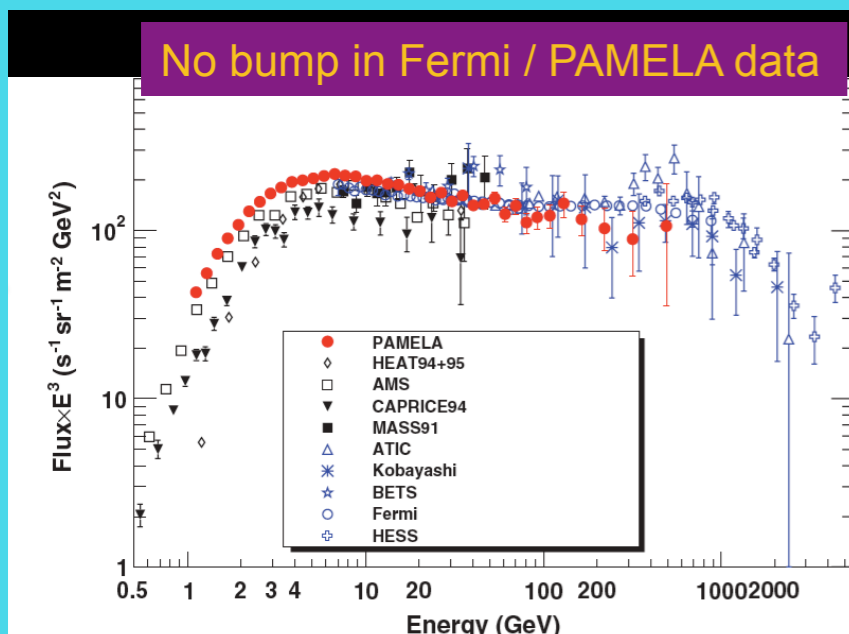
Search for the Dark Matter



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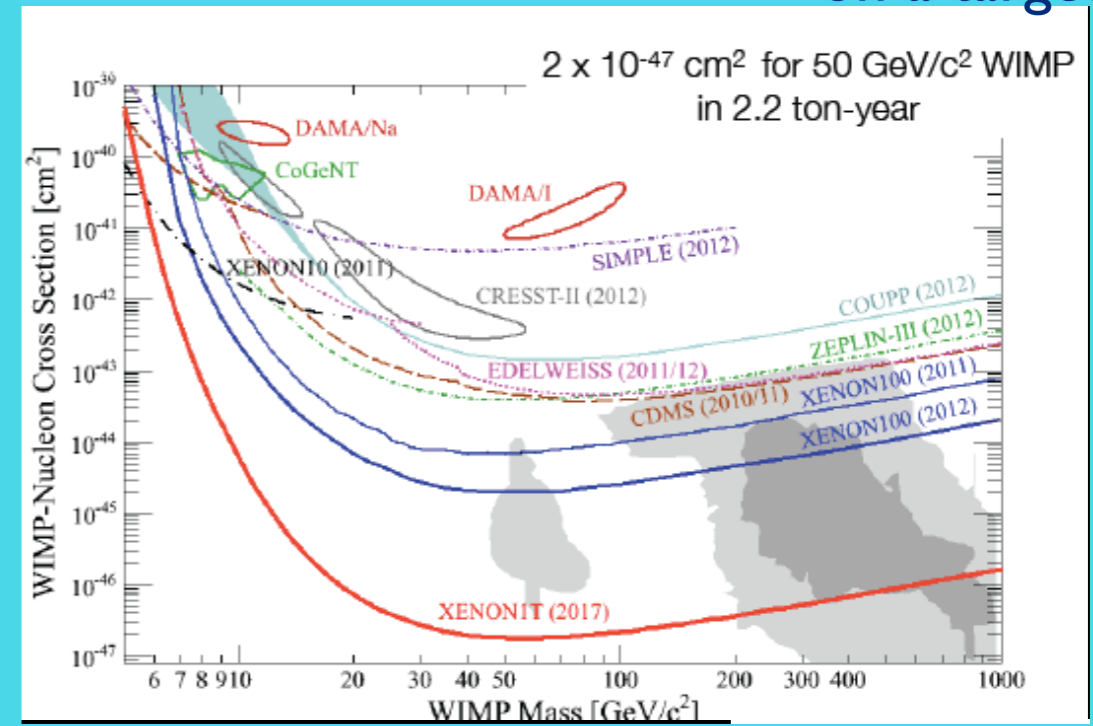
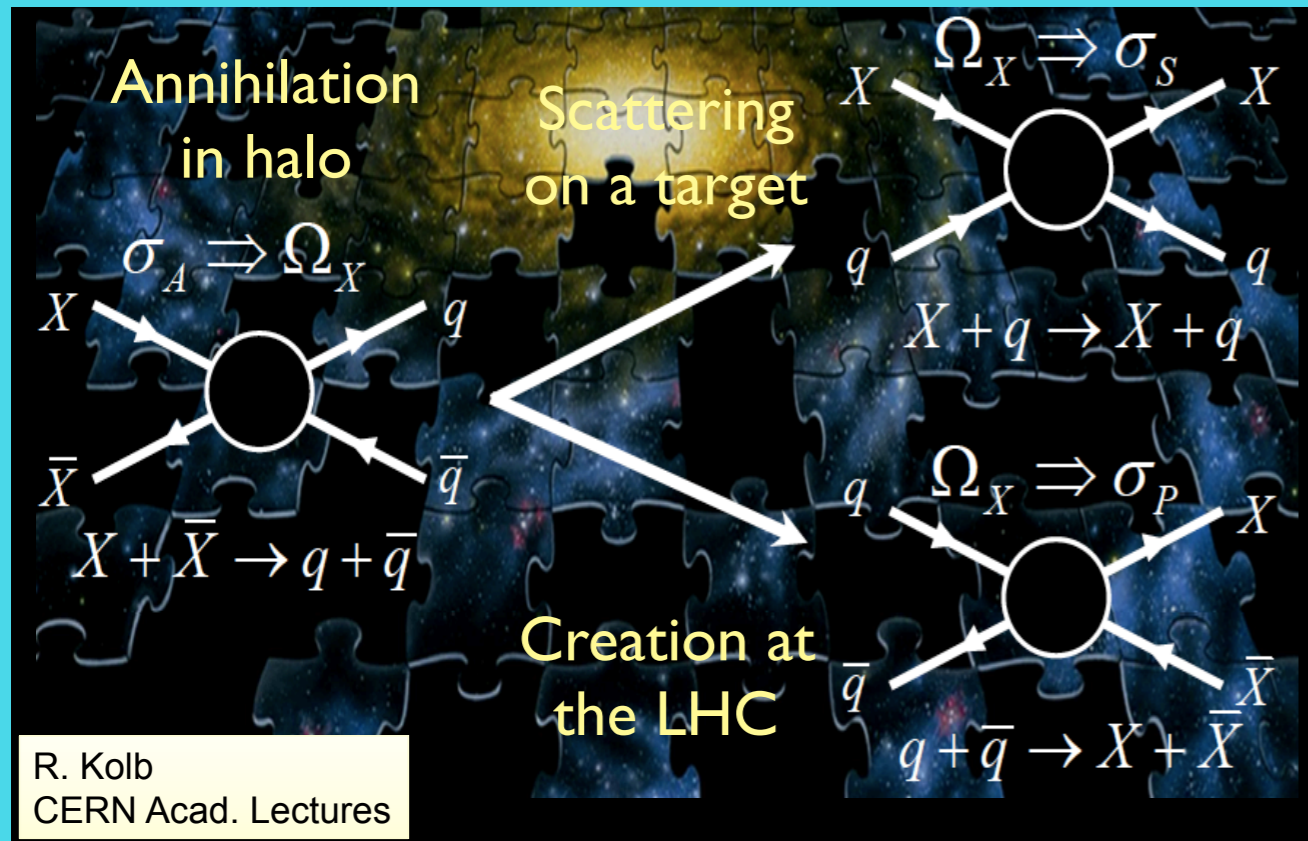


Annihilation
in halo

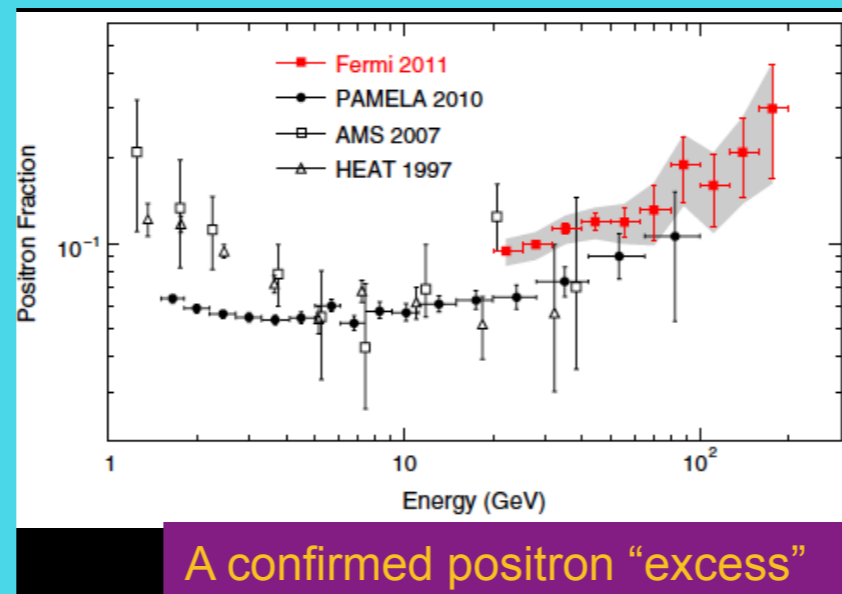
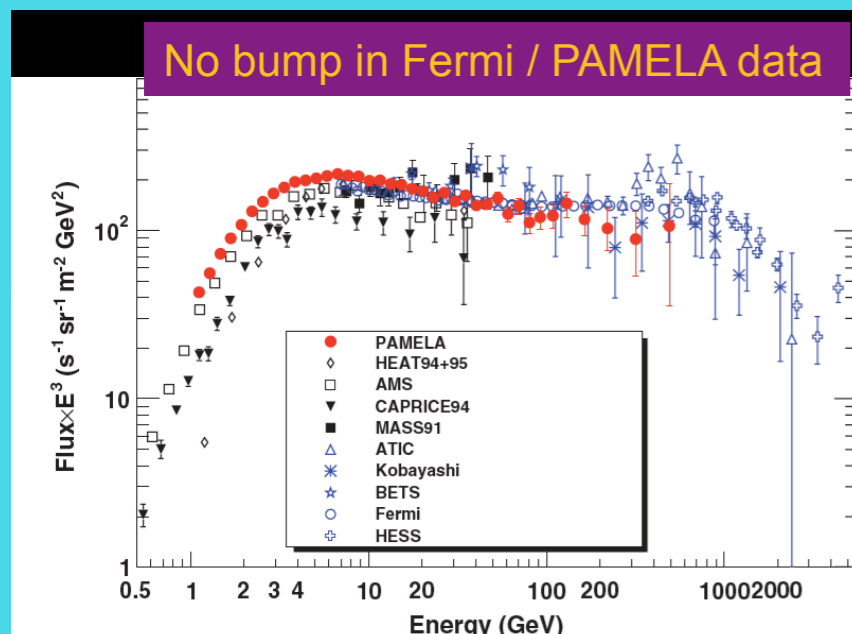


Search for the Dark Matter

Scattering
on a target

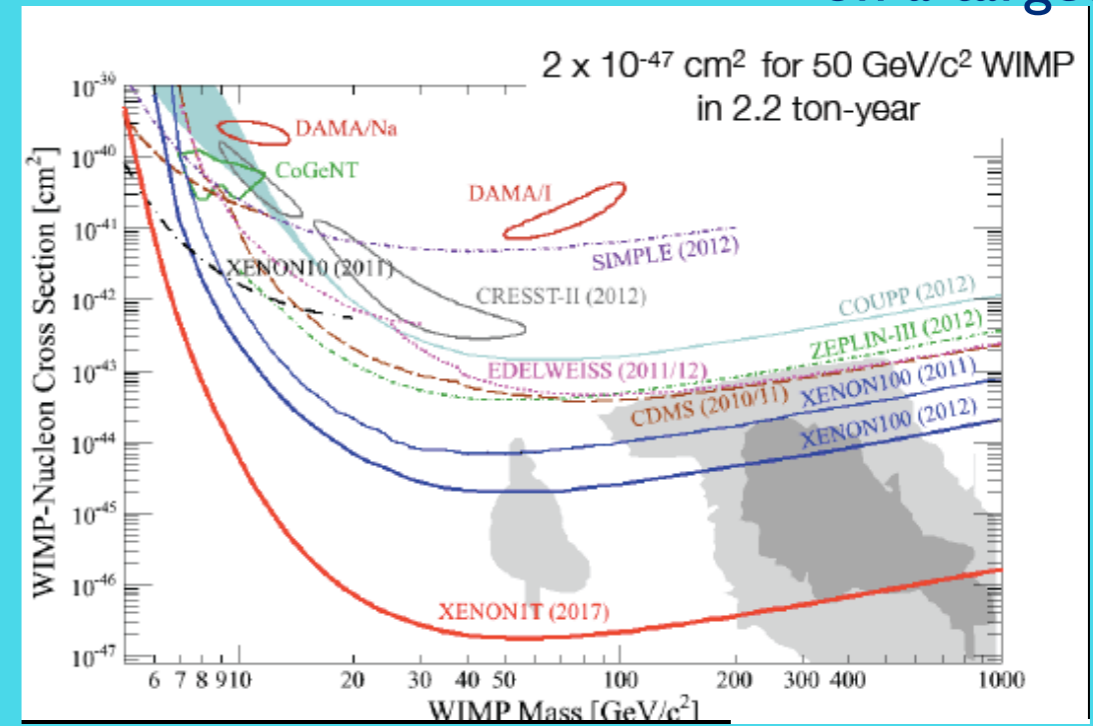
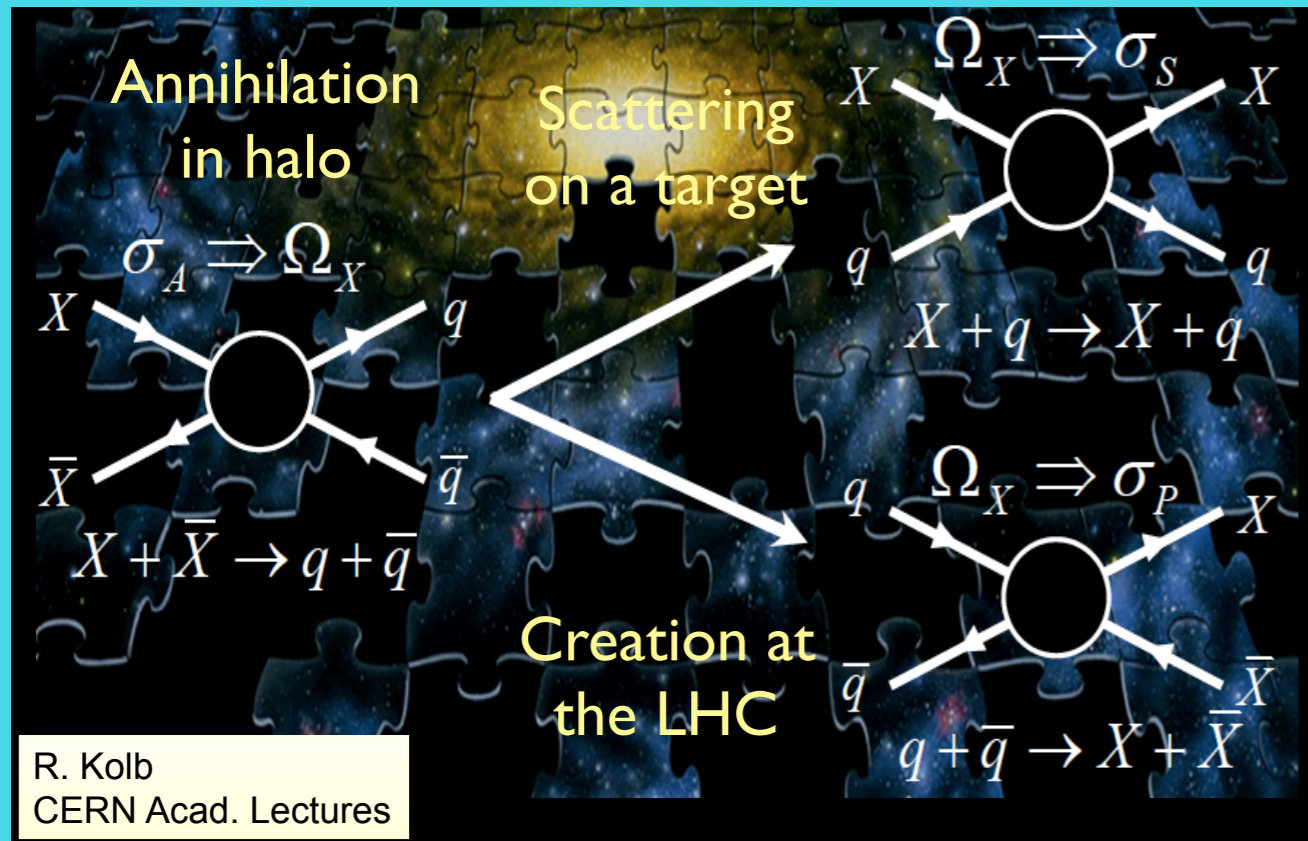


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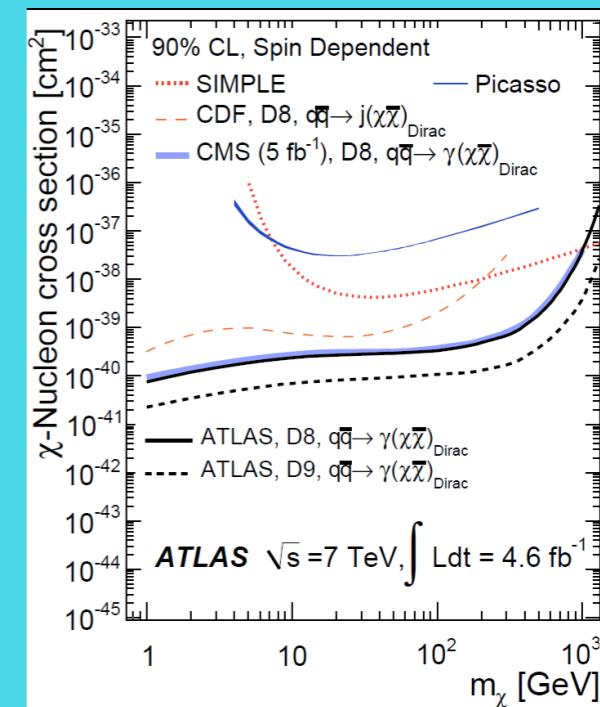
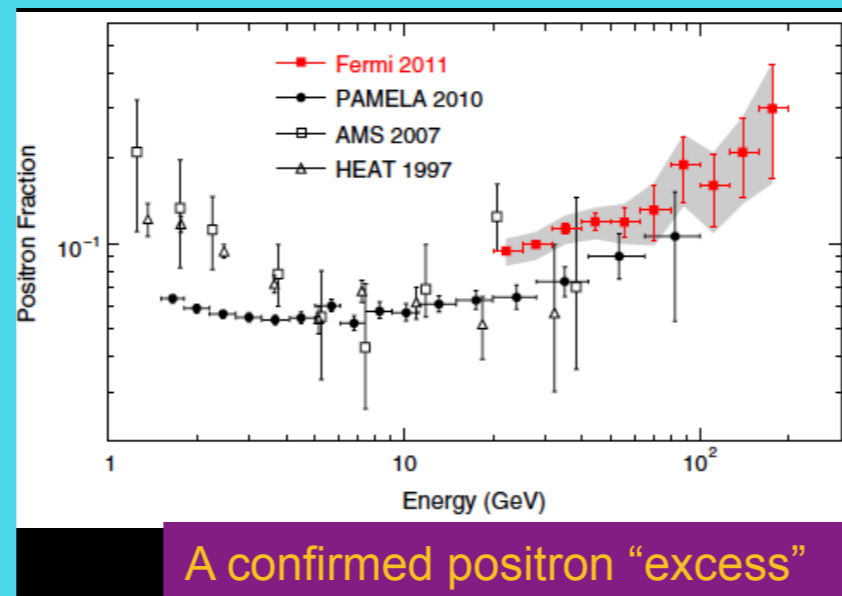
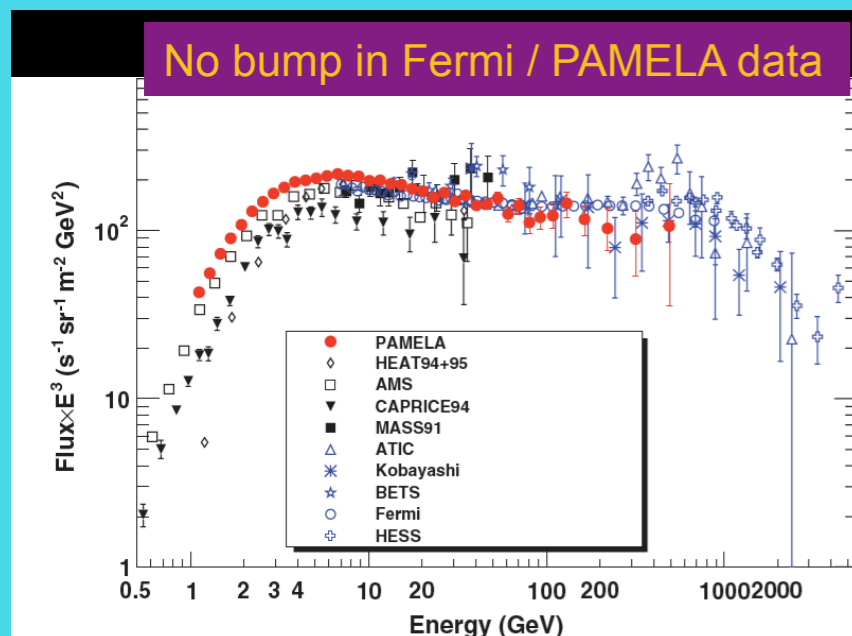
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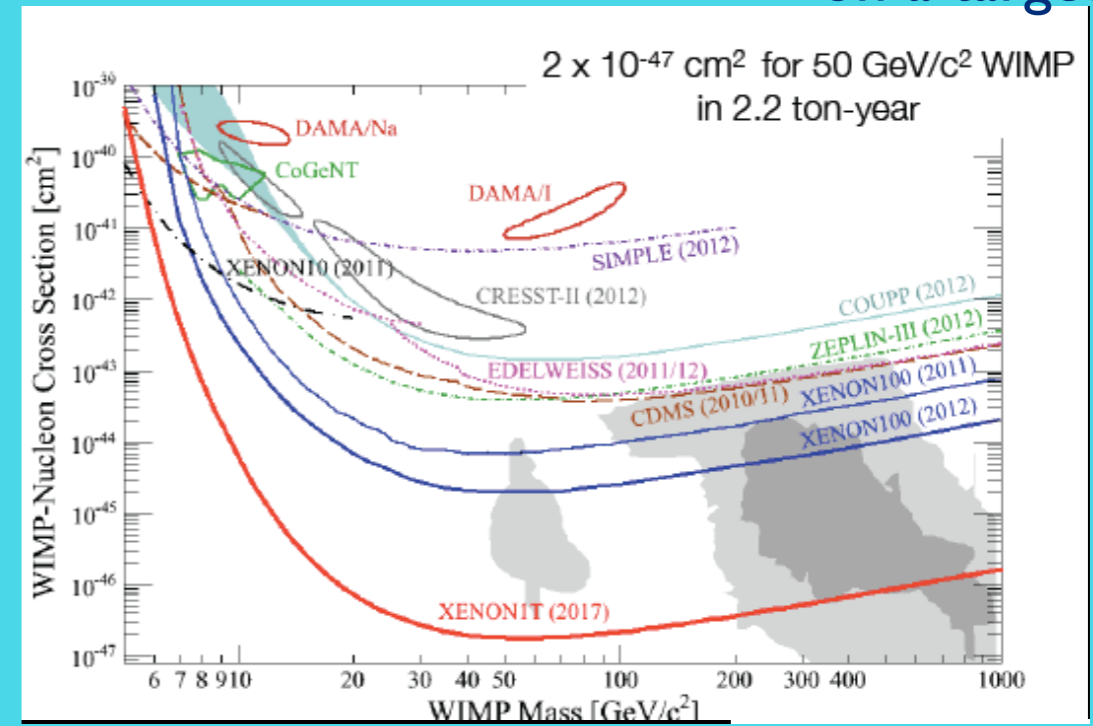
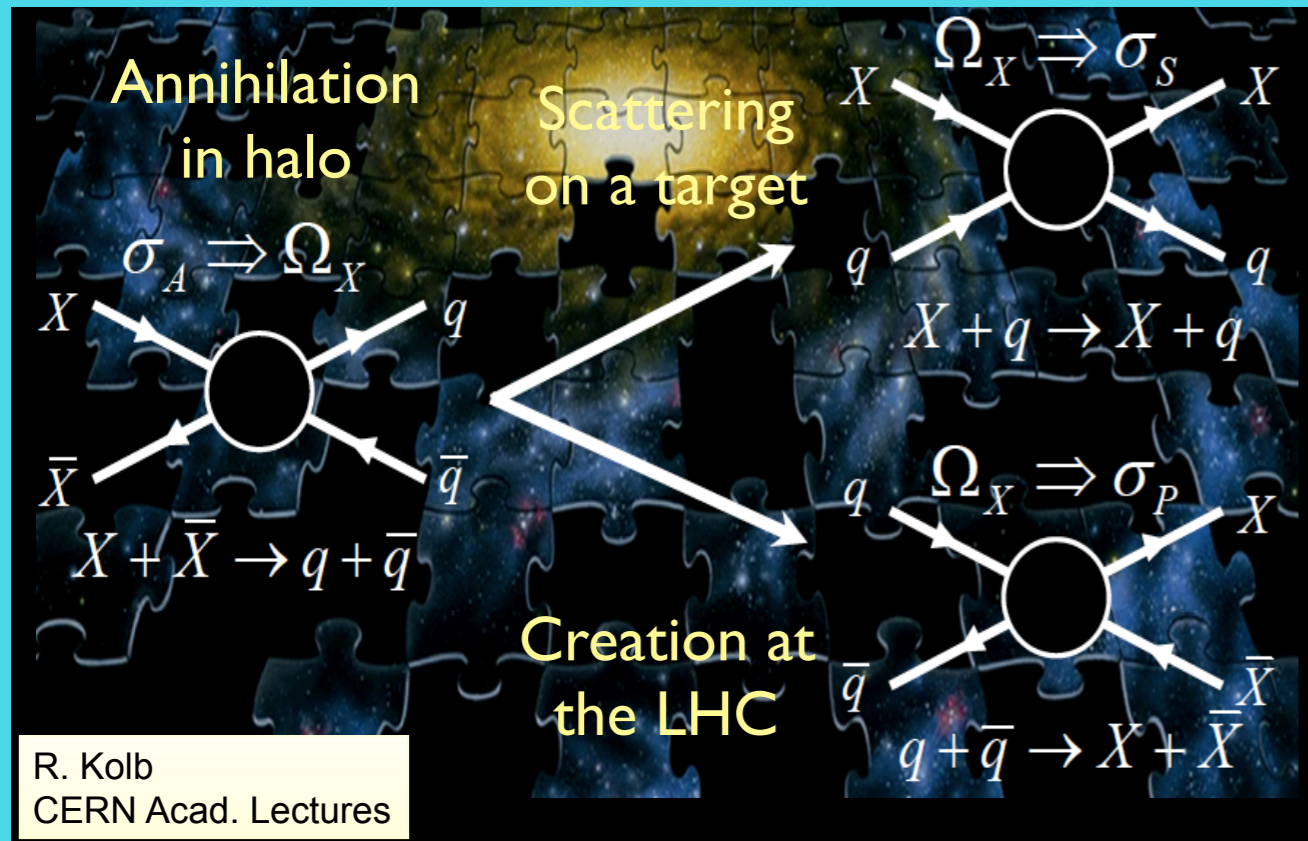
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Creation at
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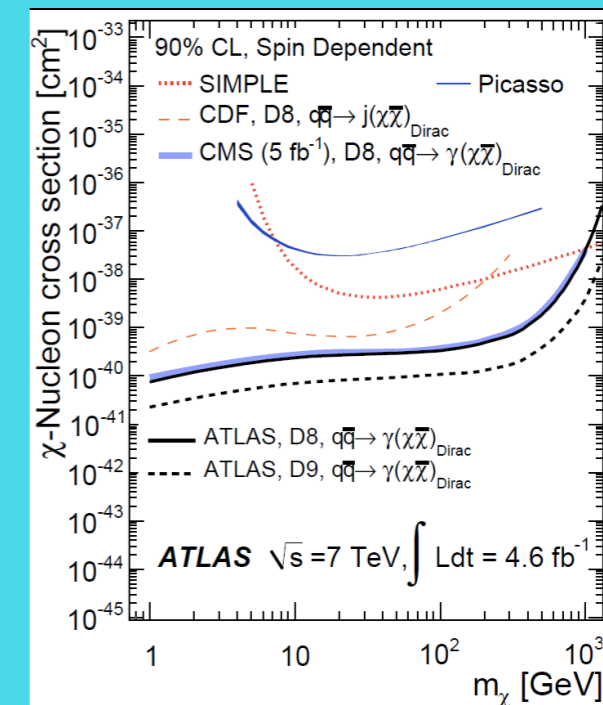
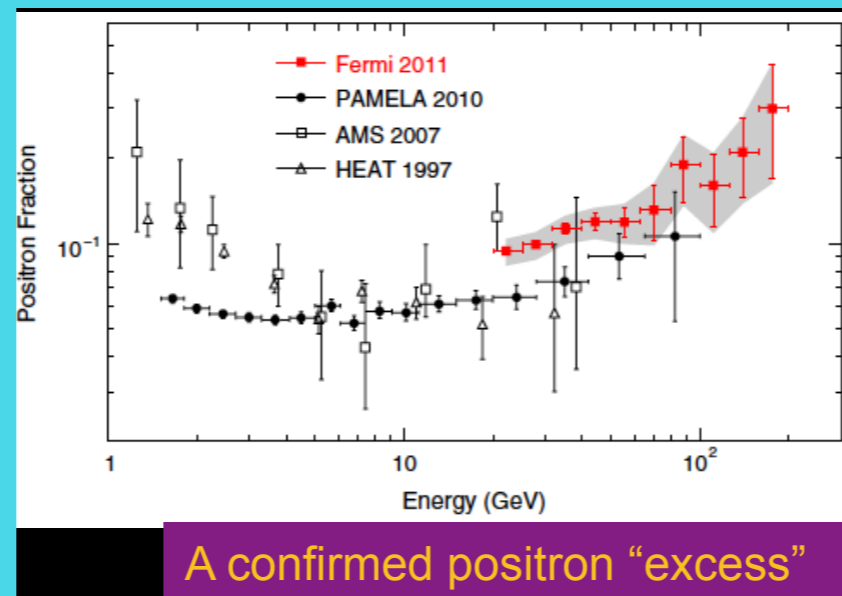
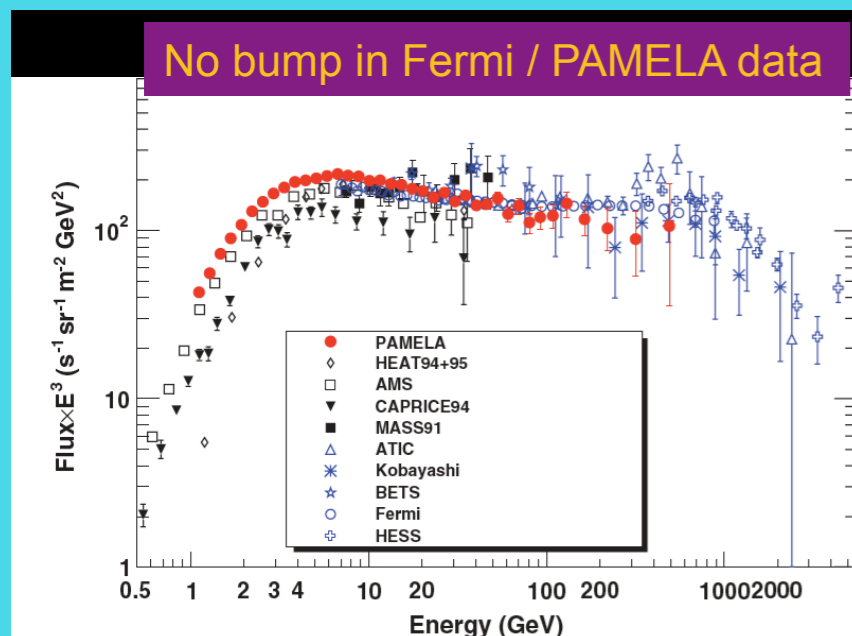
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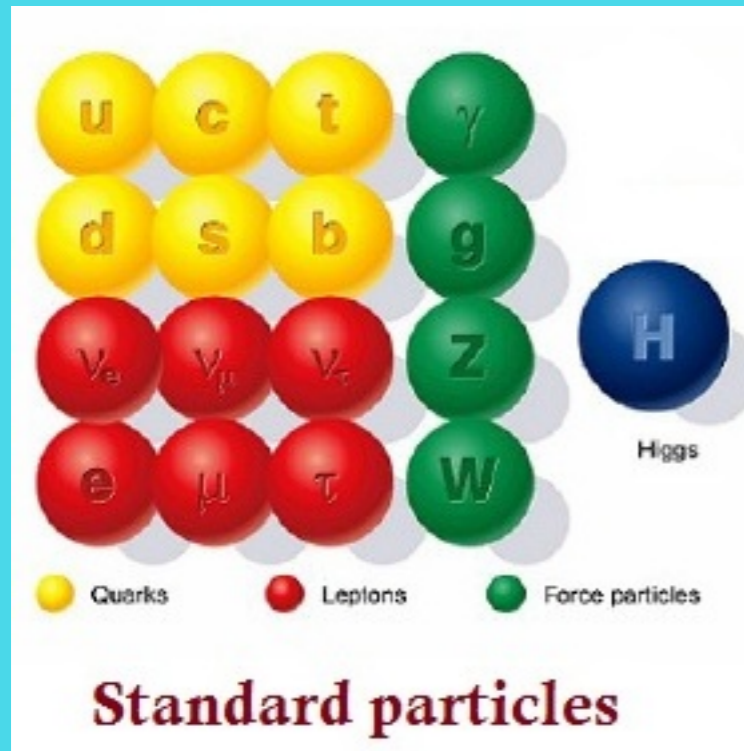
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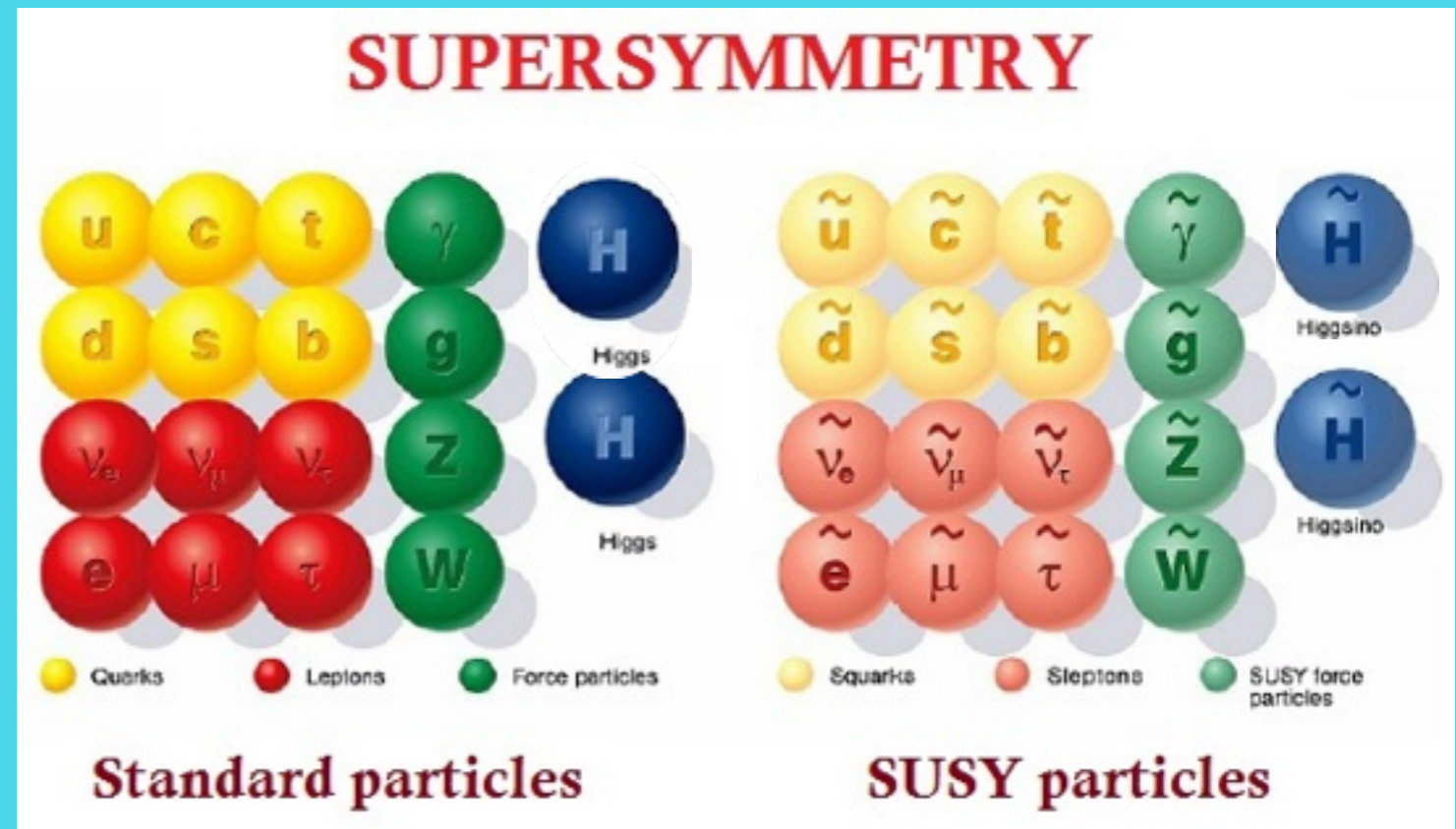
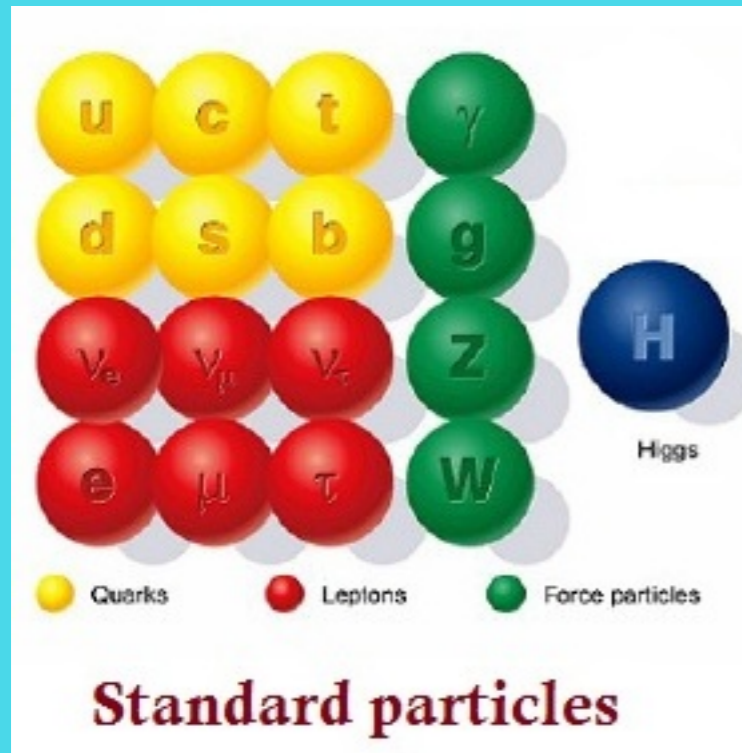


The signal is absent so far!

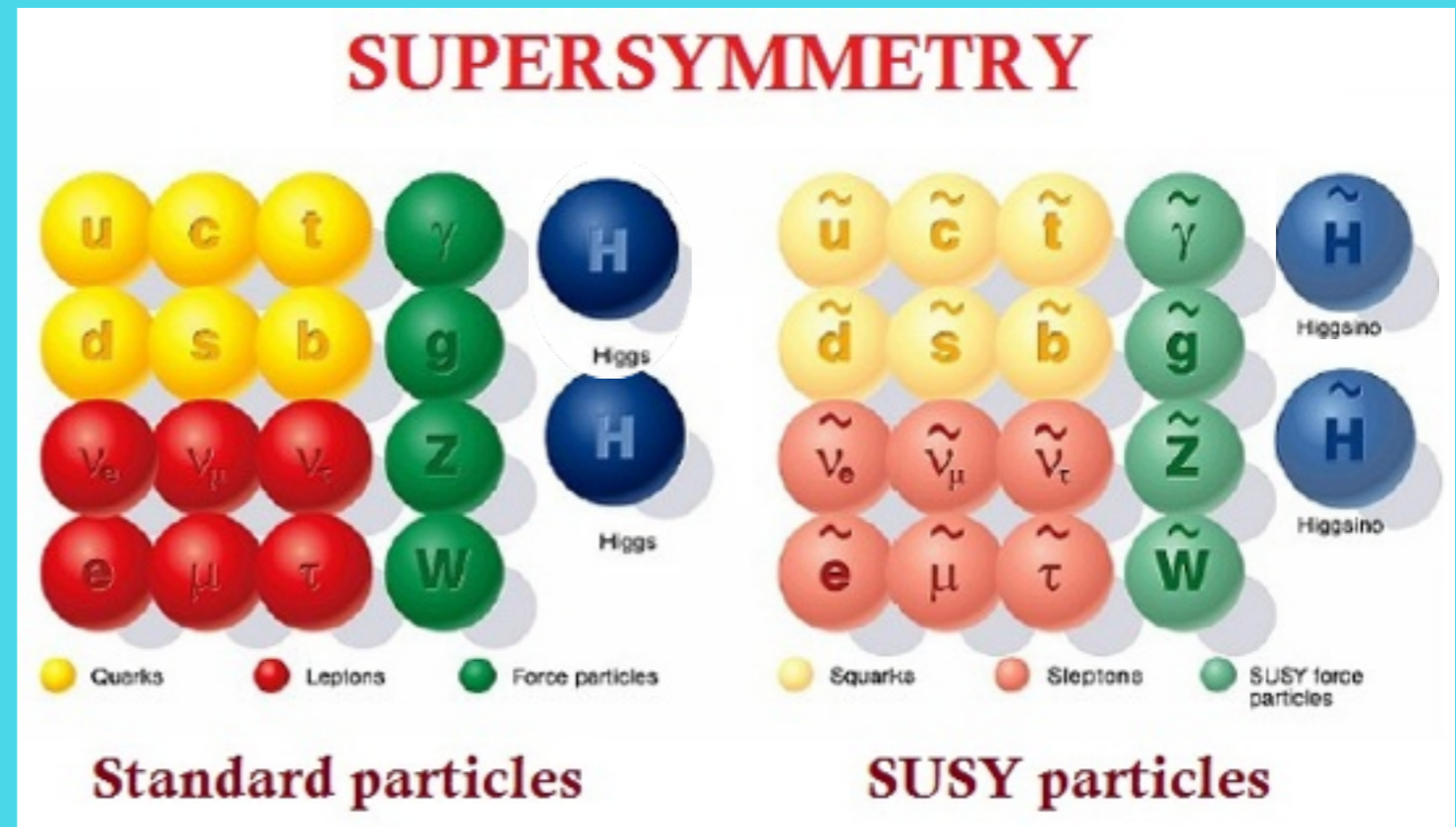
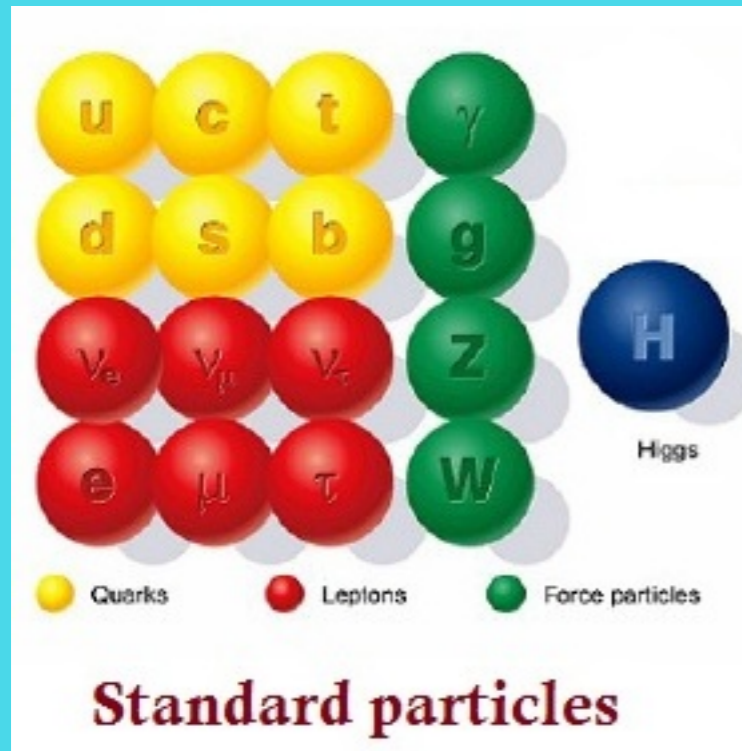
New Particles and Interactions



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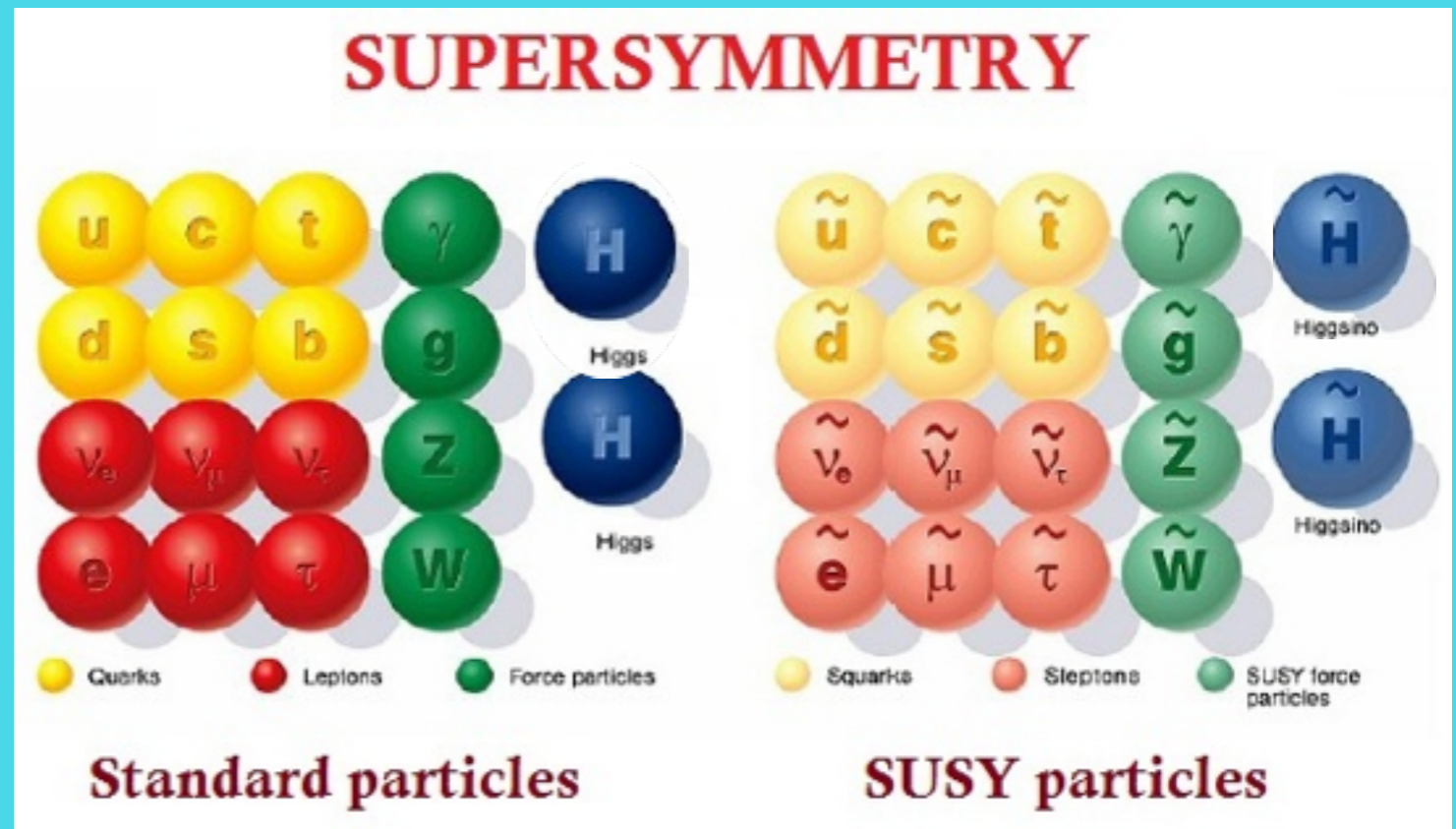
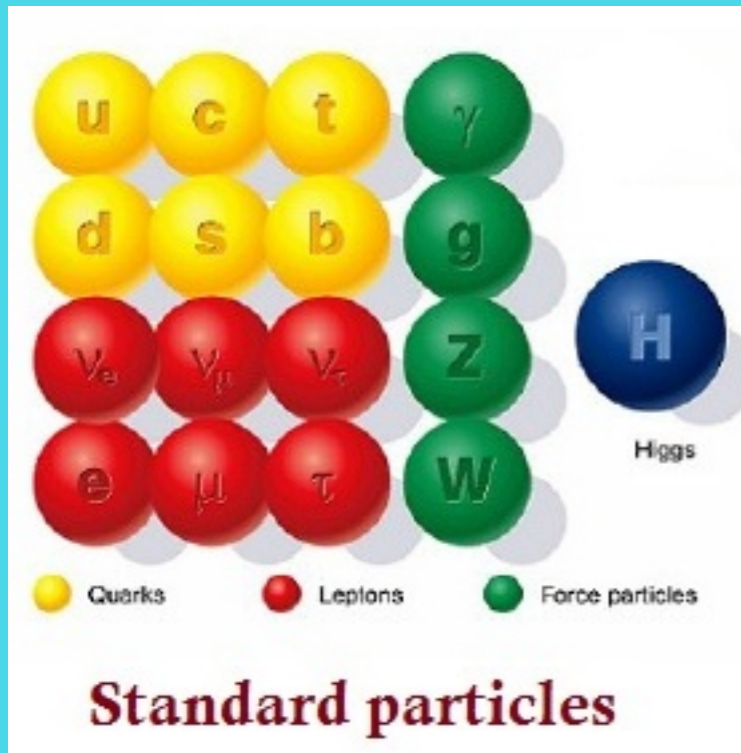


New Particles and Interactions



Supersymmetry is a dream of a unified theory of all particles and interactions

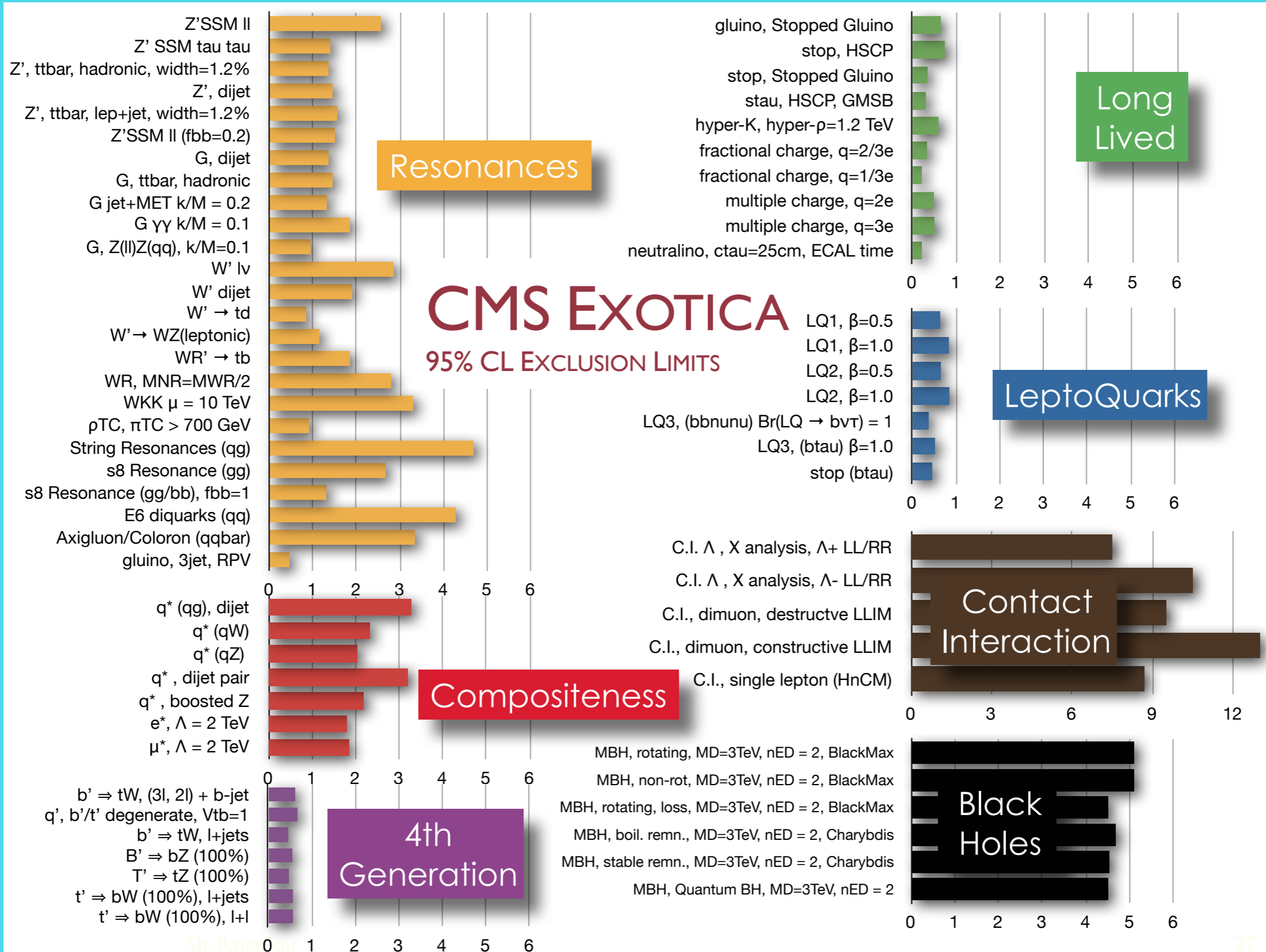
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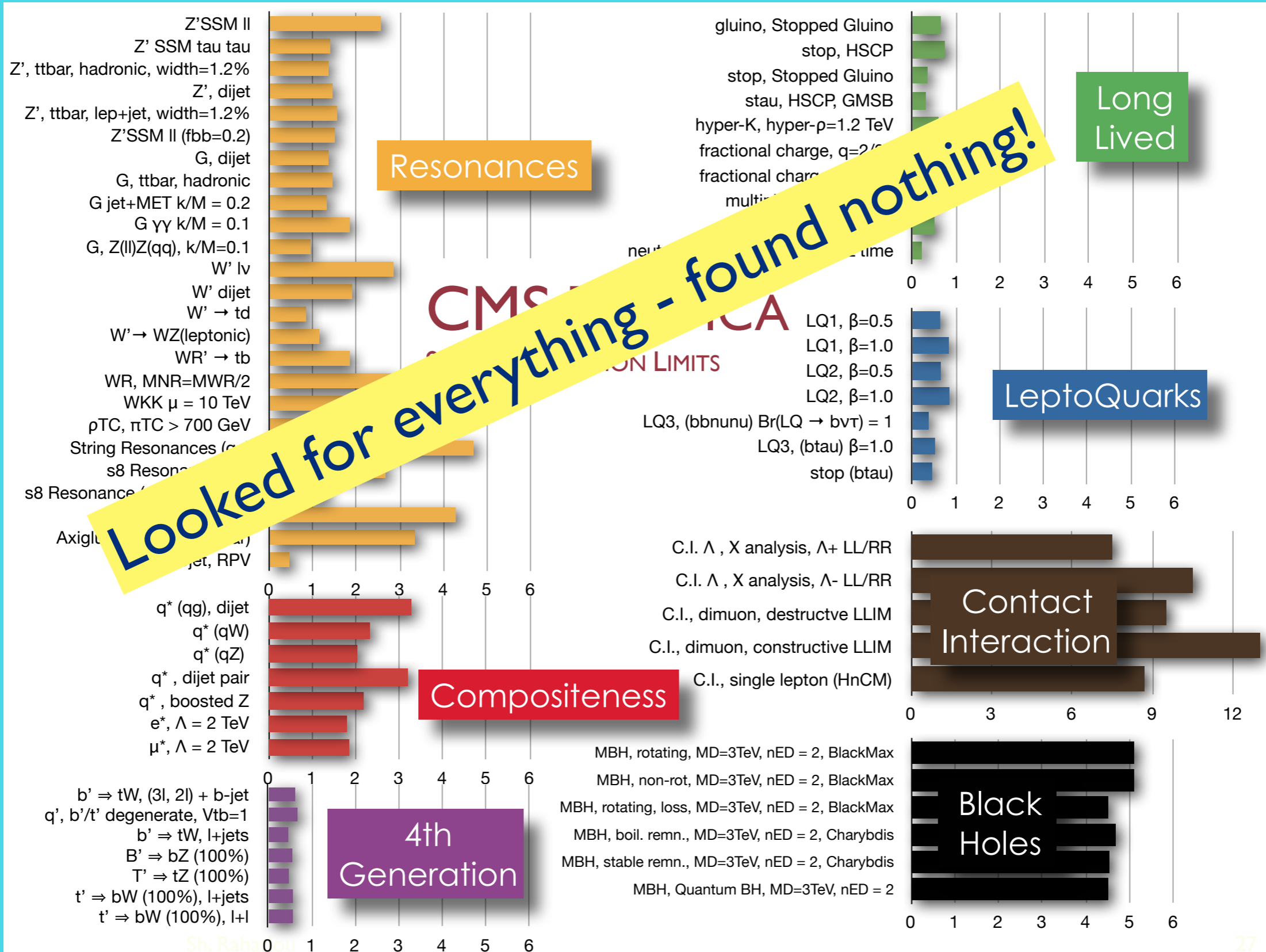
	Дальнодействующее (с безмассовым бозоном)	Короткодействующее (с массивными бозонами)	"Конфайнментовое"
Спин 0 (скалярные поля)		Хиггсовское $V(r) \sim \frac{A}{r} e^{-Br}$	
Спин 1 (векторные поля)	Электромагнитное $V(r) \sim \frac{A}{r}$	Слабое $V(r) \sim \frac{A}{r} e^{-Br}$	Сильное $V(r) \sim \frac{A}{r} + Cr$
Спин 2 (тензорные поля)	Гравитационное $V(r) \sim \frac{A}{r}$		

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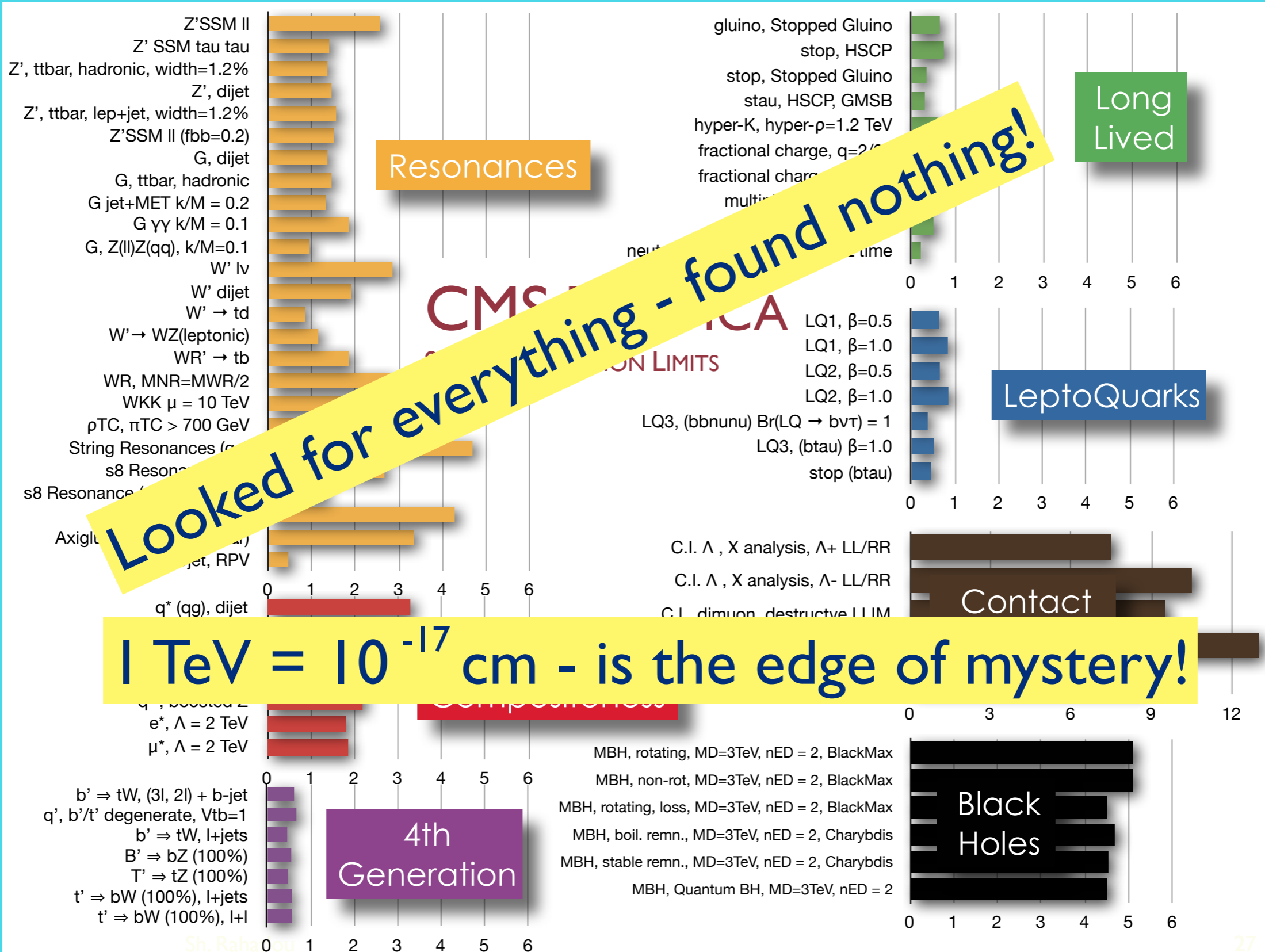
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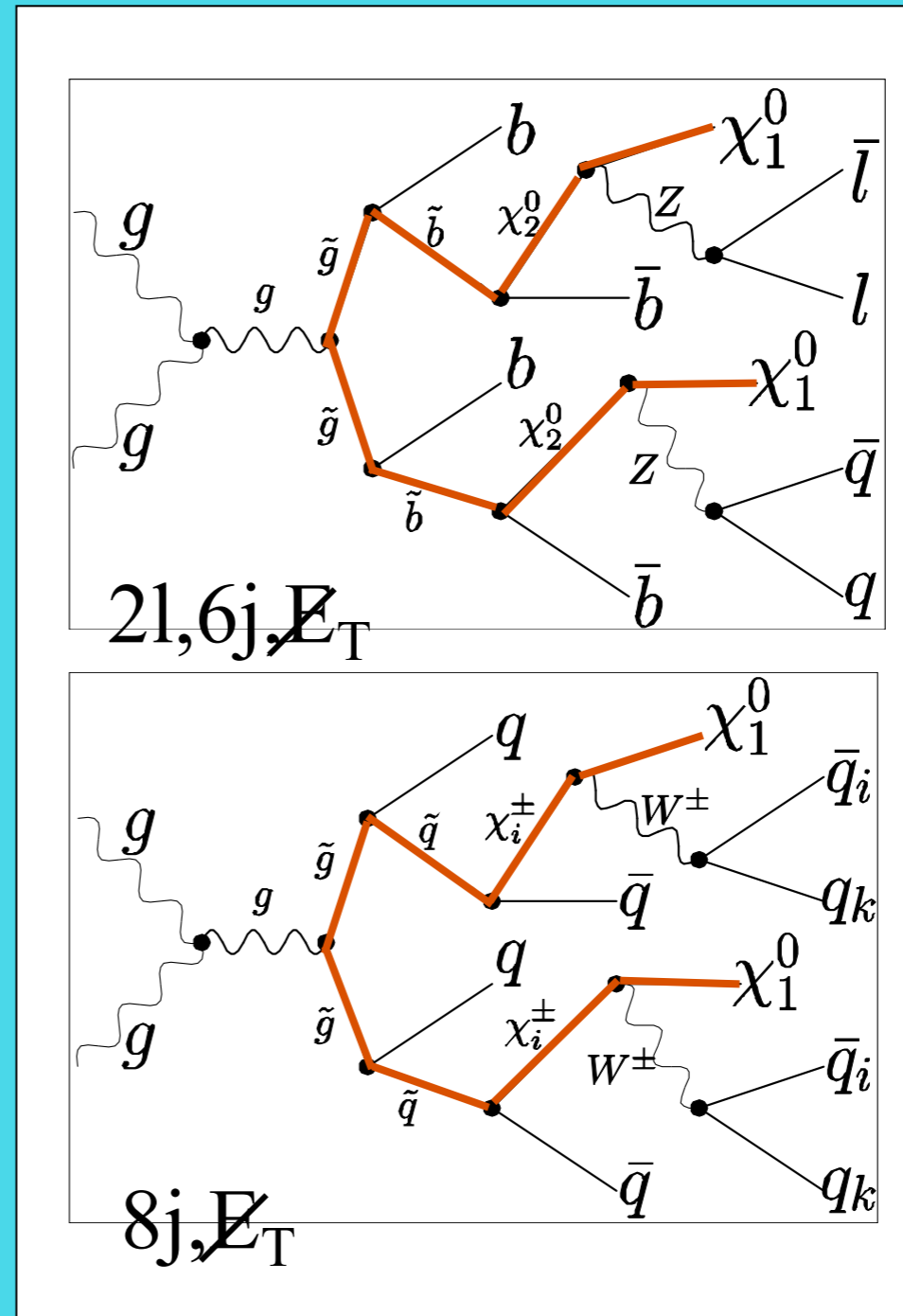
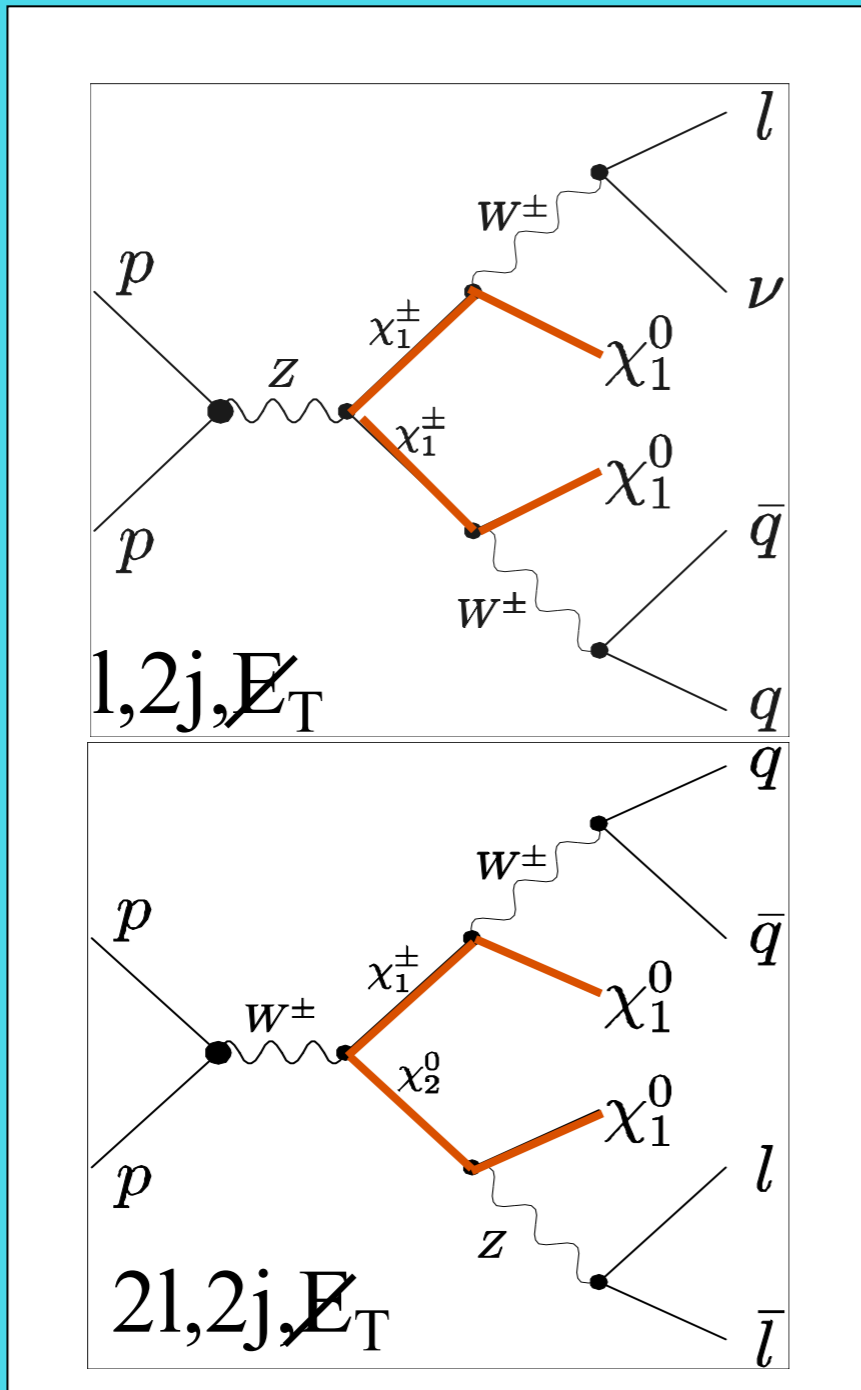


New Particles and Interactions



Creation and decay of superpartners @ LHC

weak int's

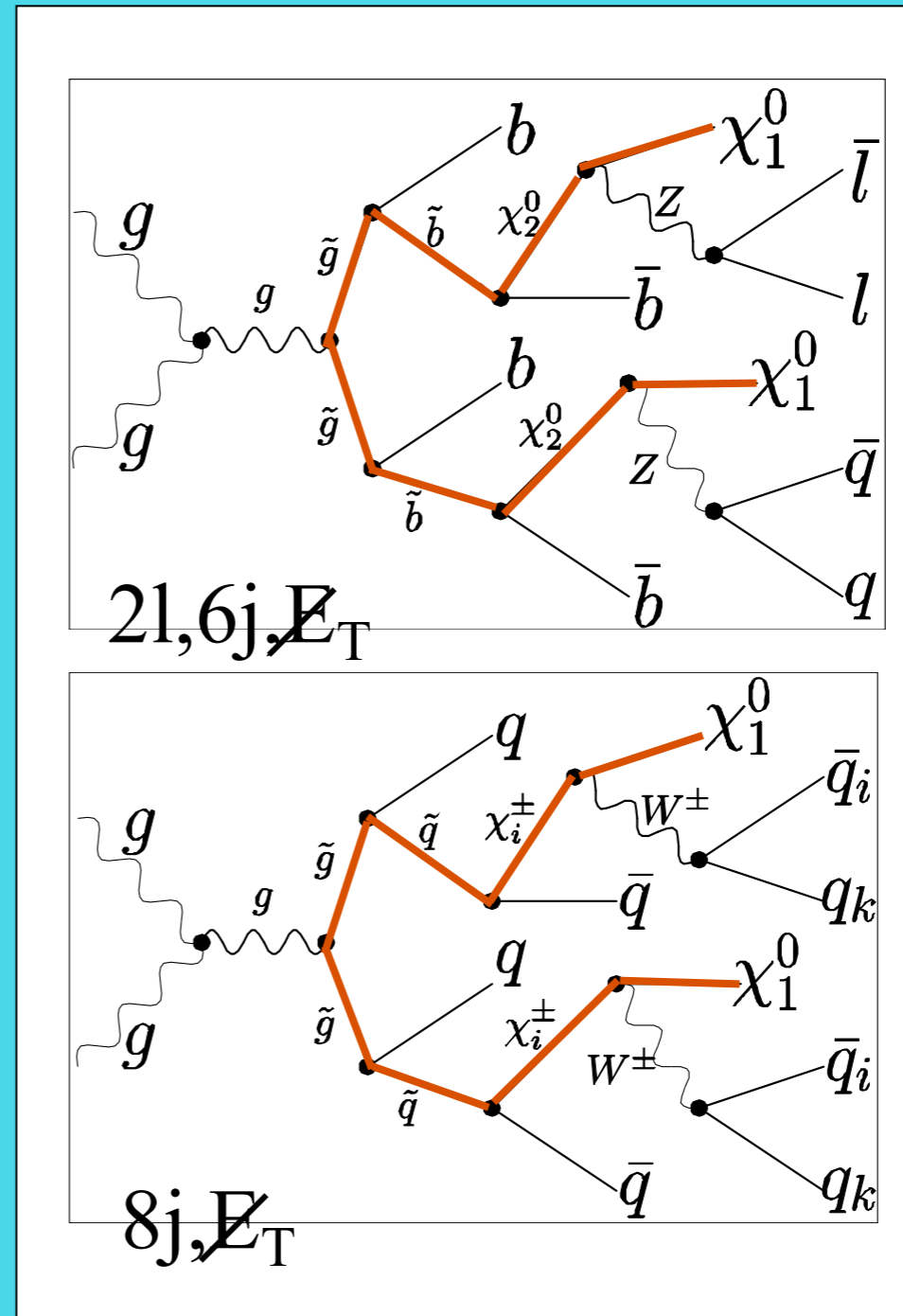
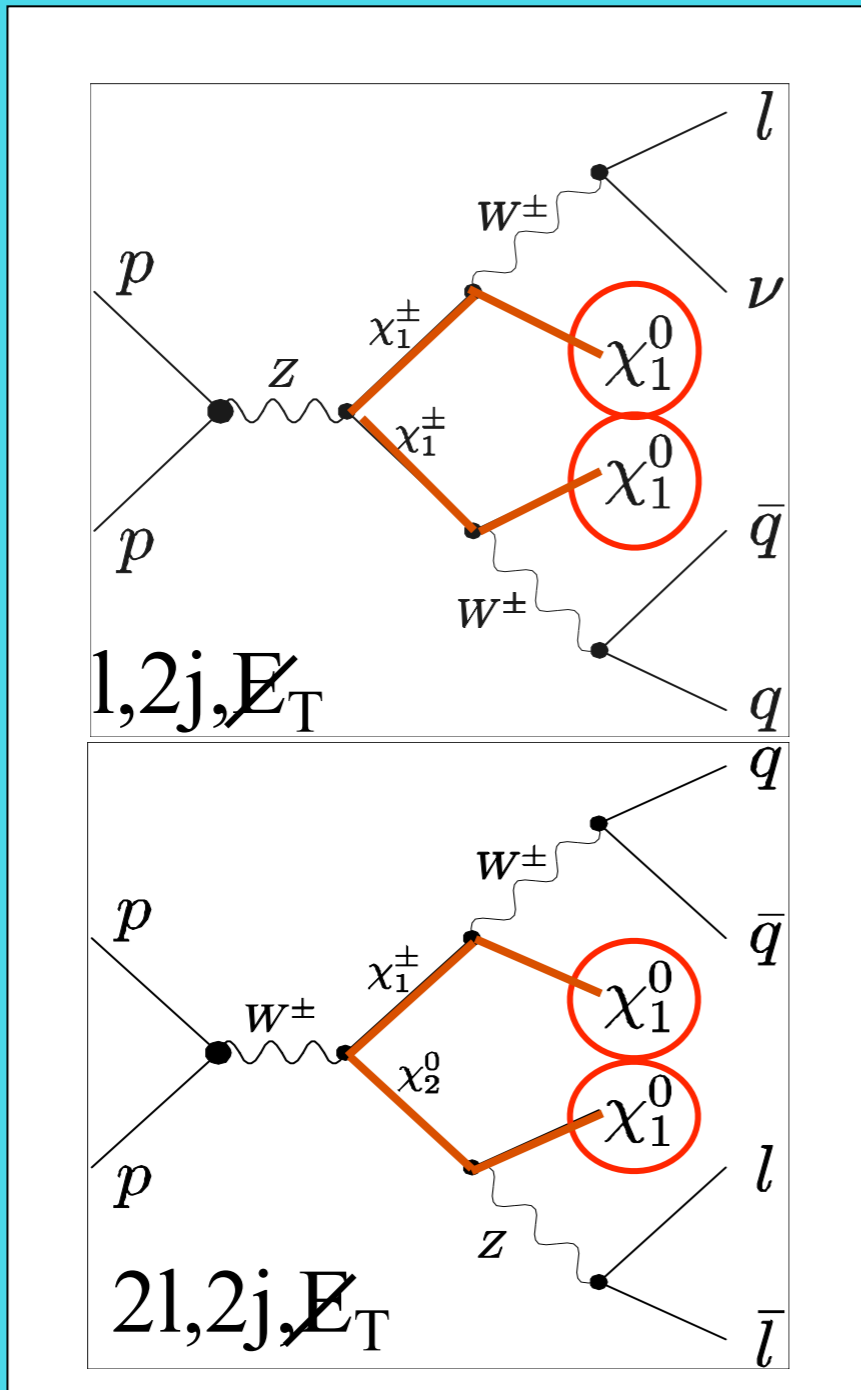


Strong int's

Typical SUSY signature: missing energy and transverse momentum

Creation and decay of superpartners @ LHC

weak int's

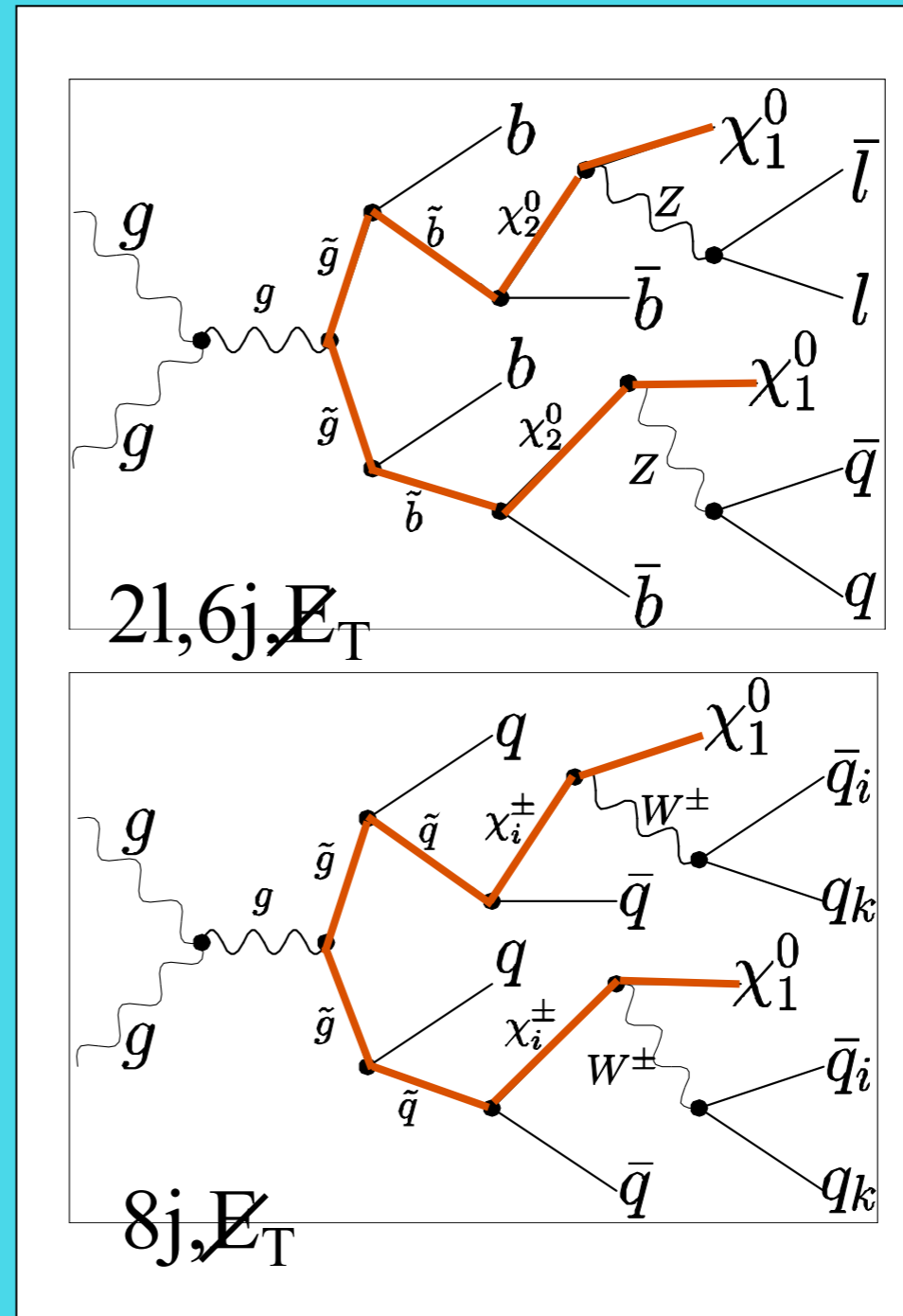
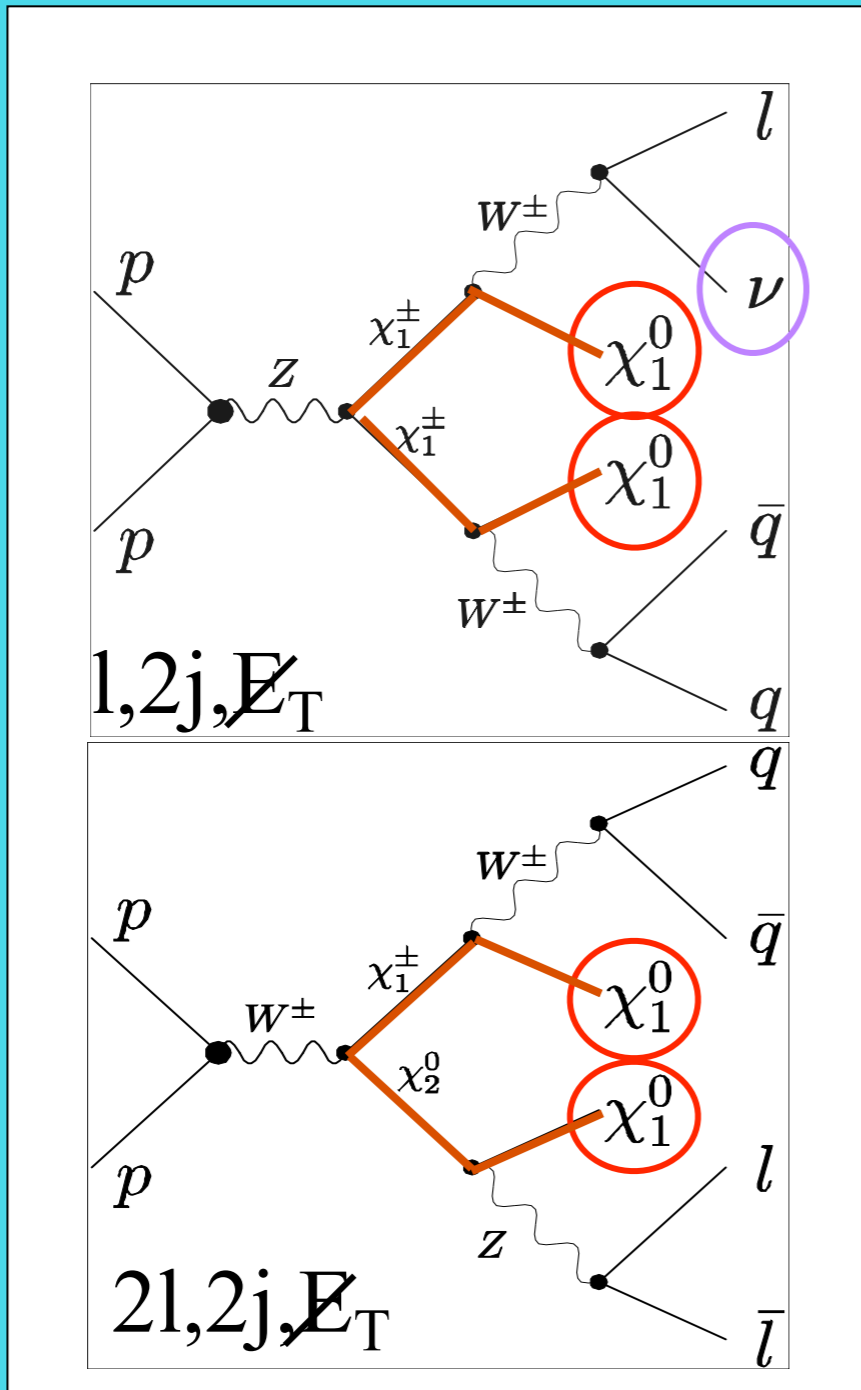


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Creation and decay of superpartners @ LHC

weak int's

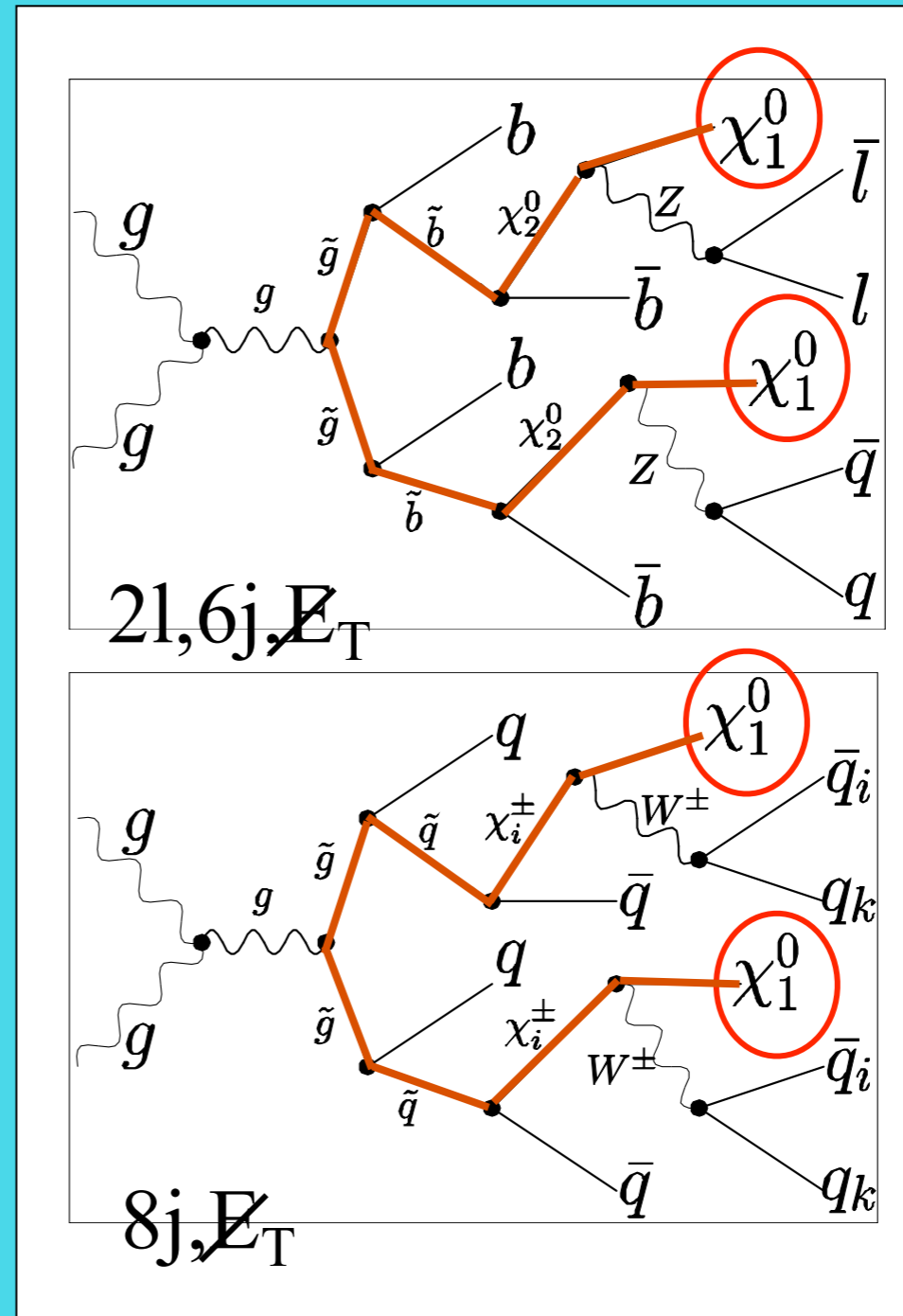
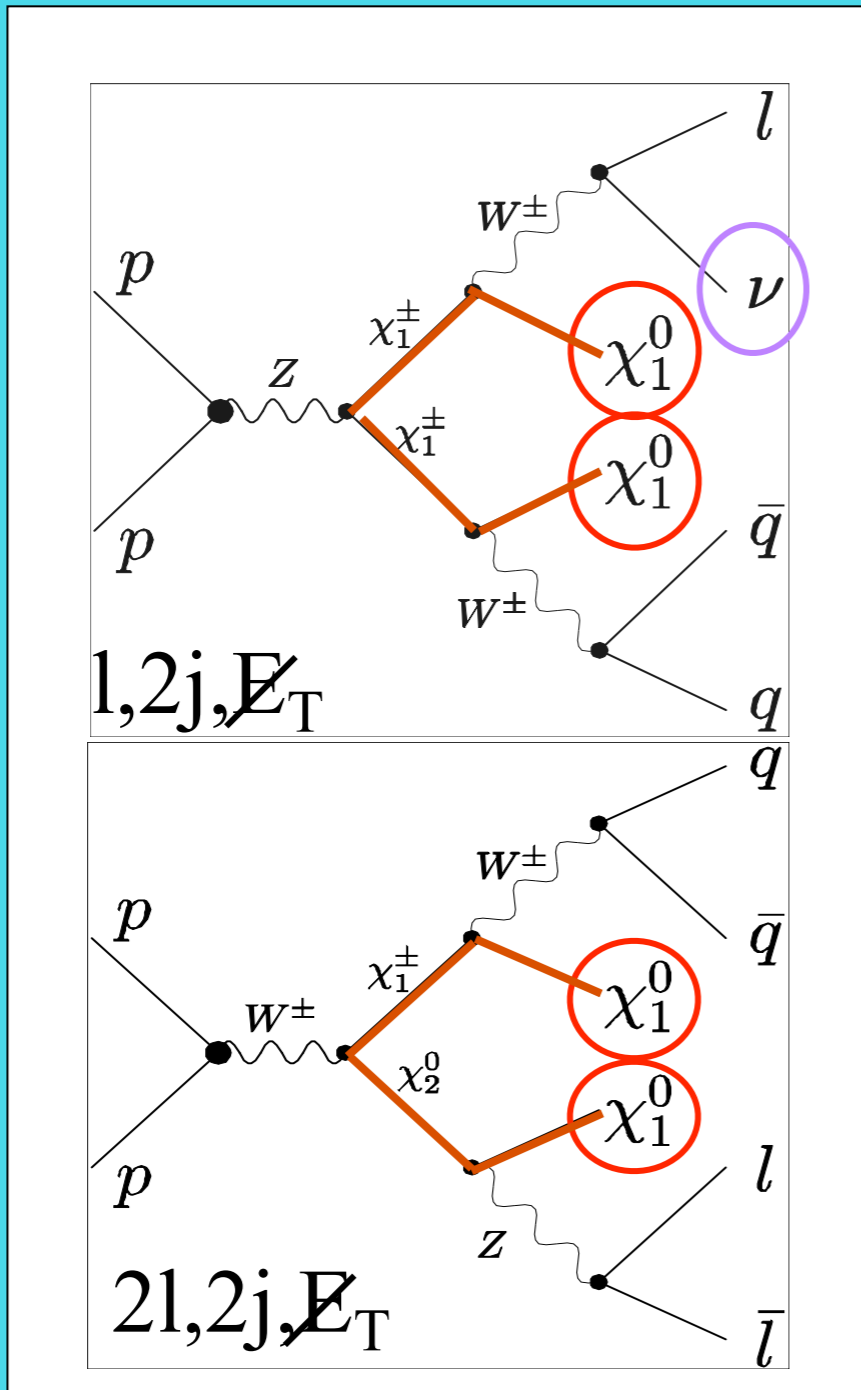


Strong int's

Typical SUSY signature: missing energy and transverse momentum

Creation and decay of superpartners @ LHC

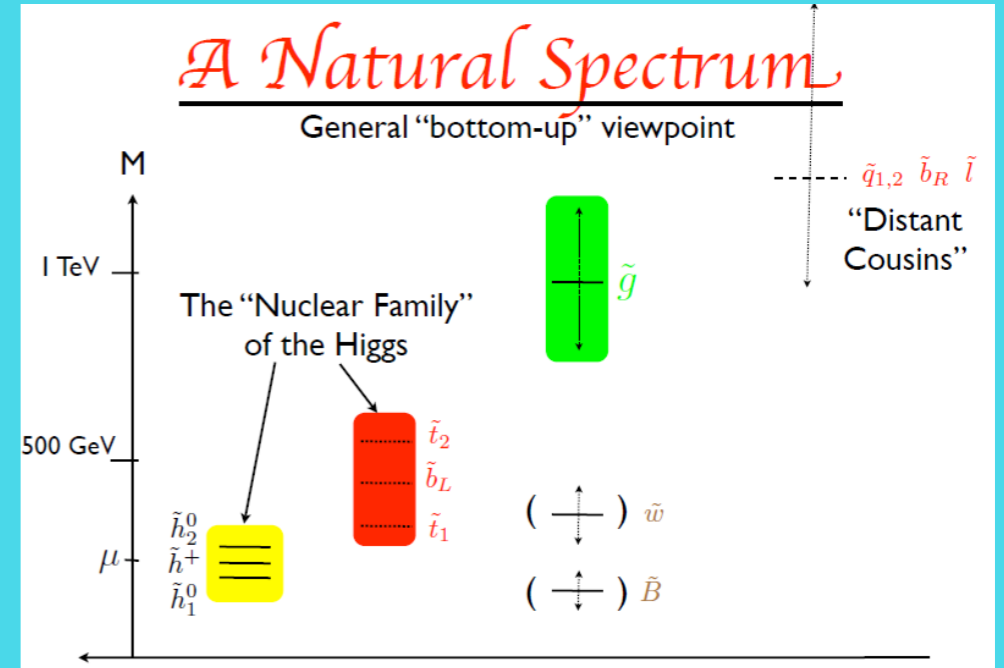
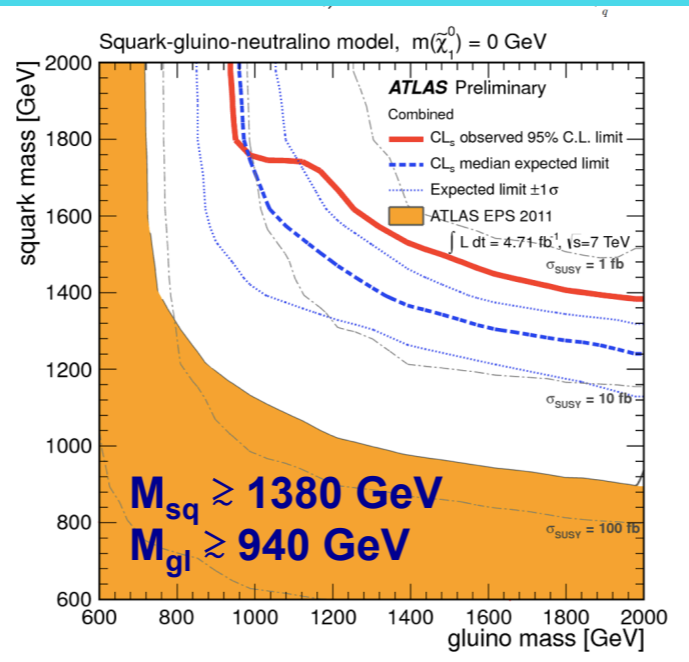
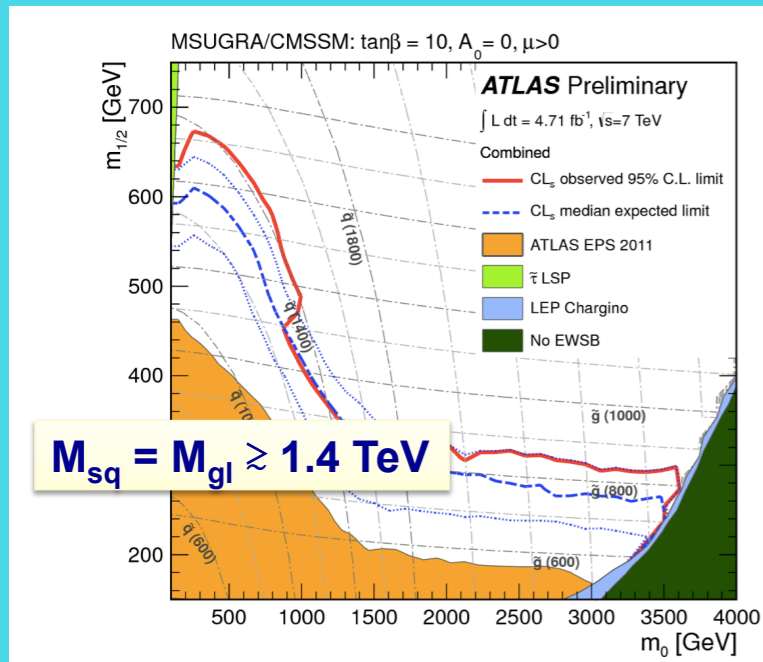
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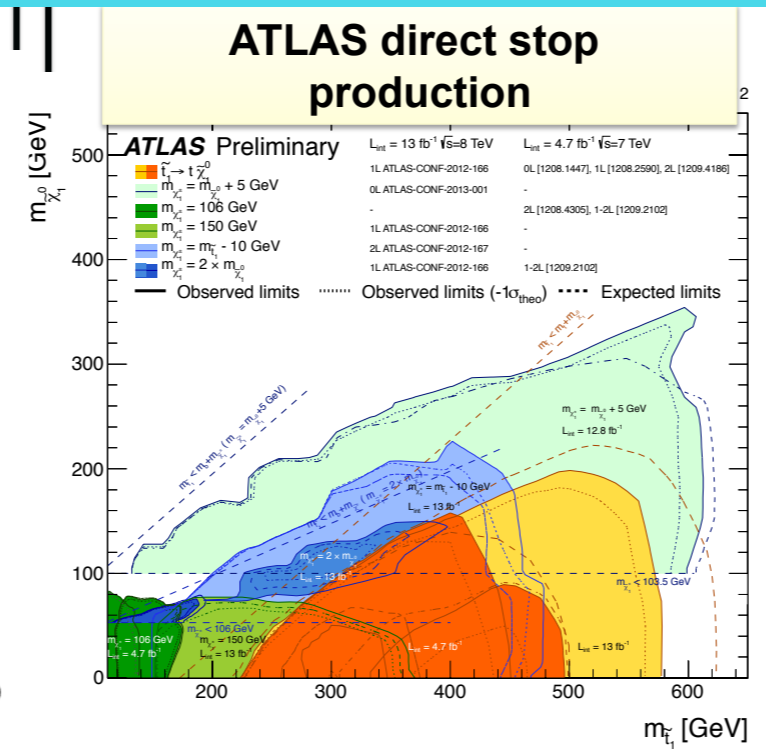
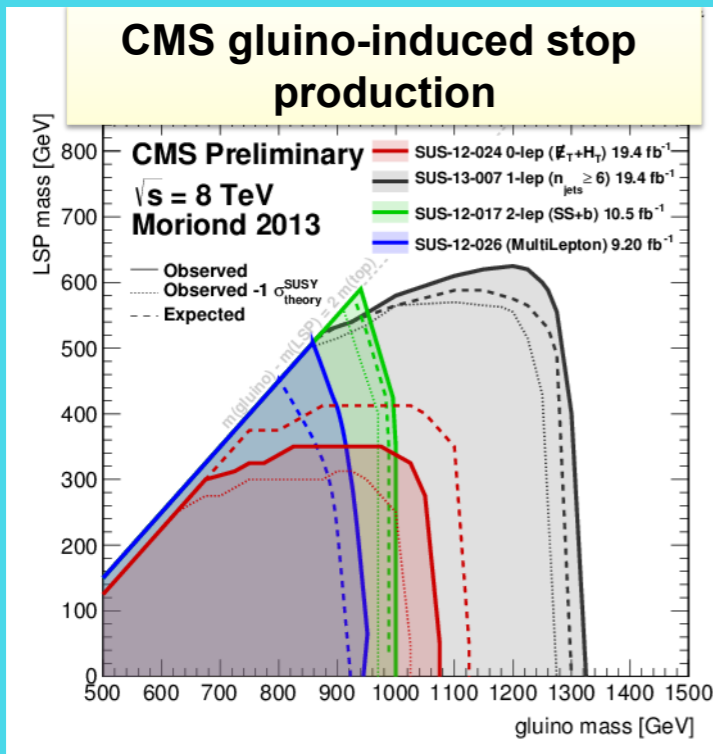
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Typical SUSY signature: missing energy and transverse momentum

Search for Supersymmetry @ LHC

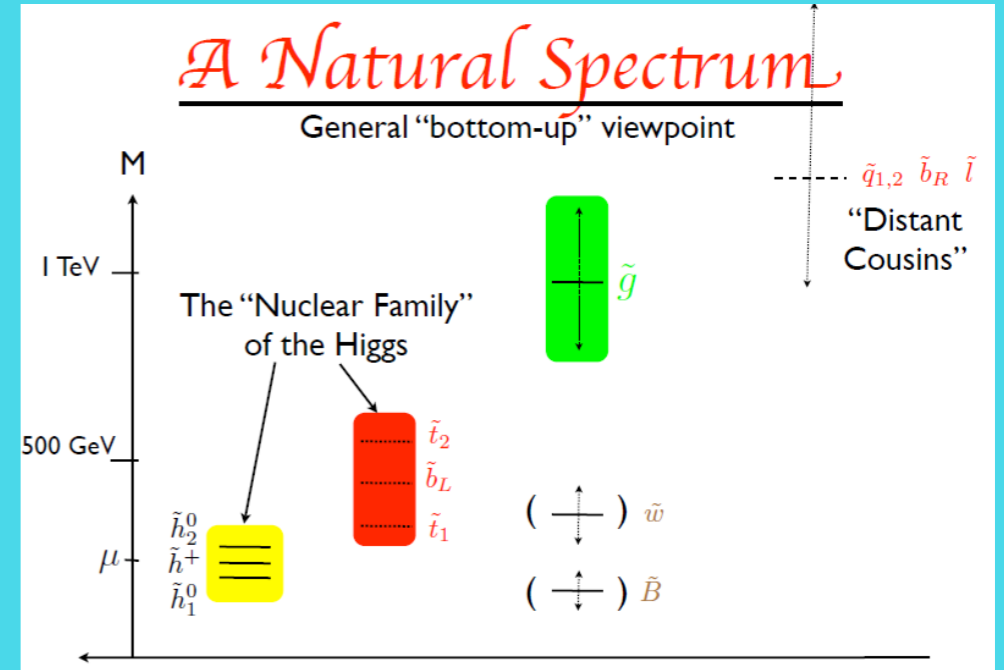
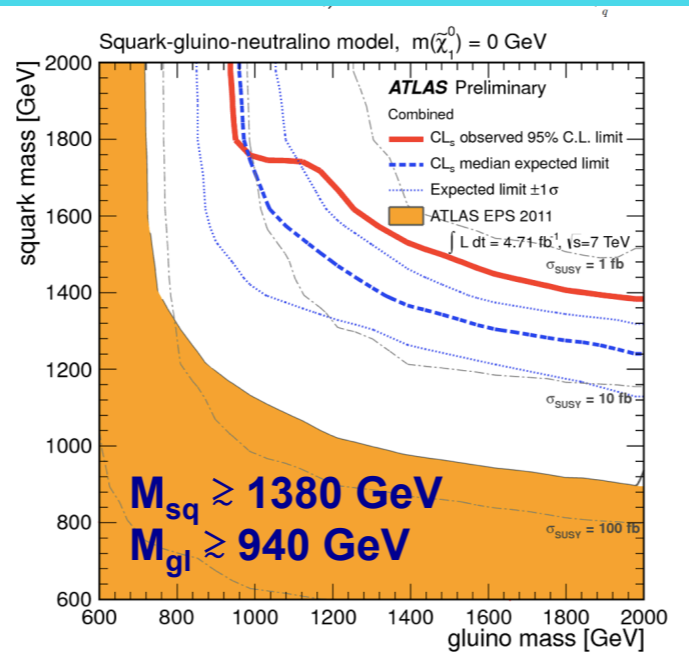
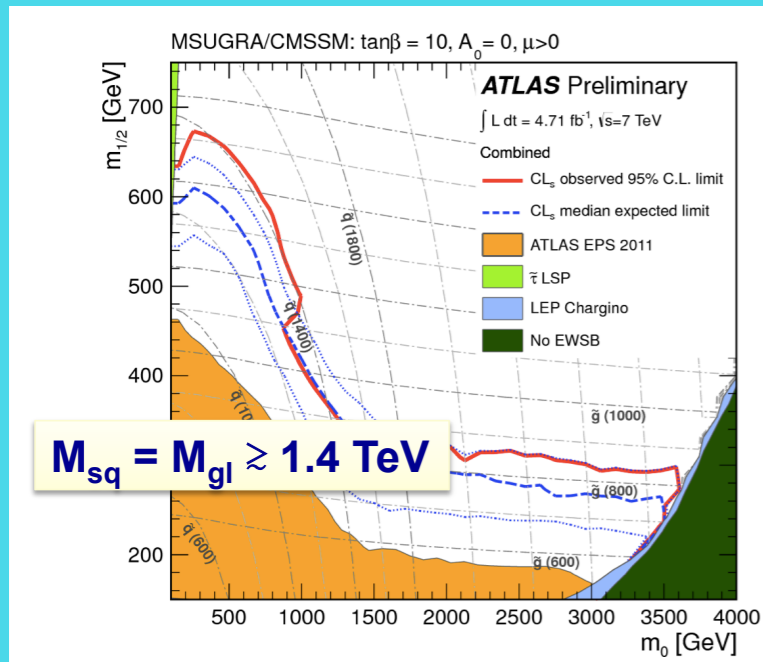


Weakly interacting particles

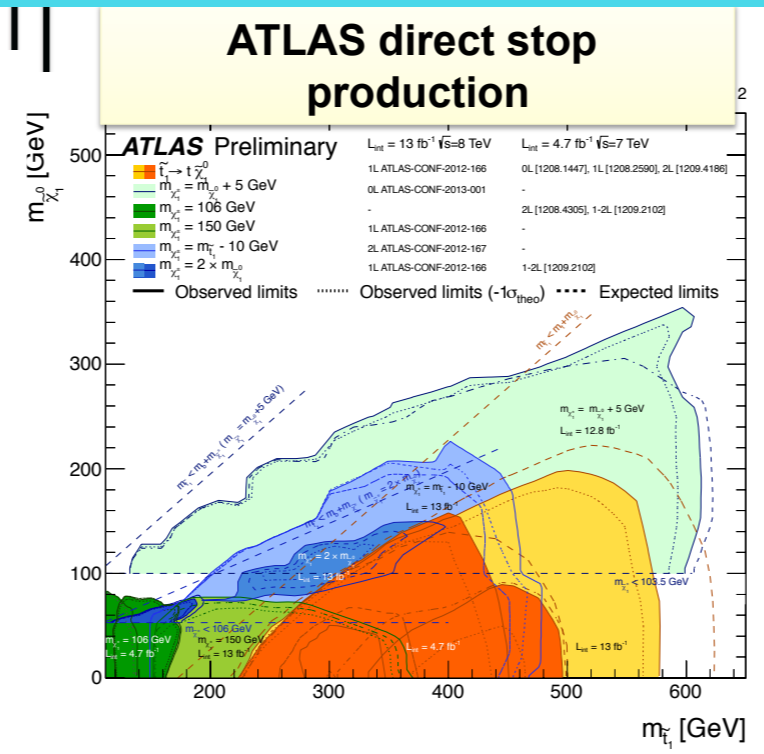
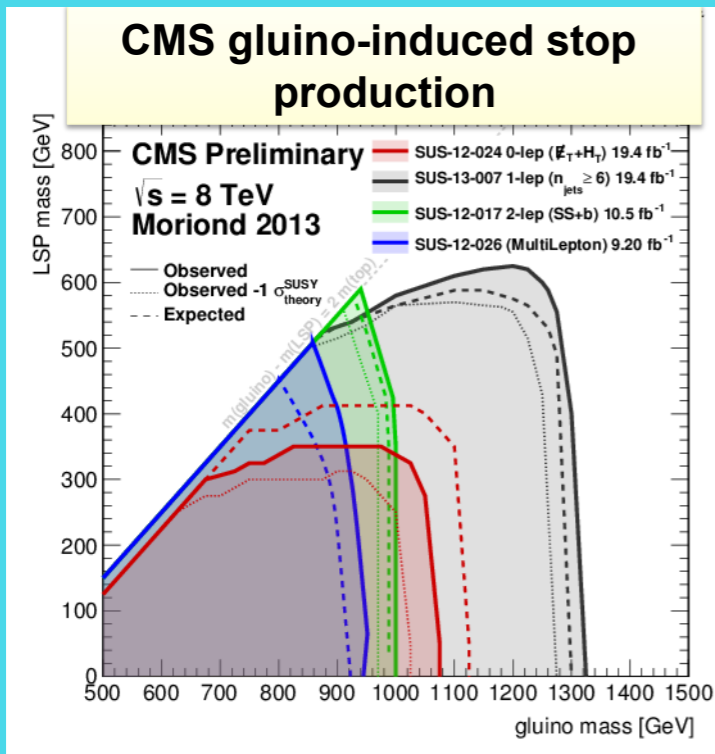


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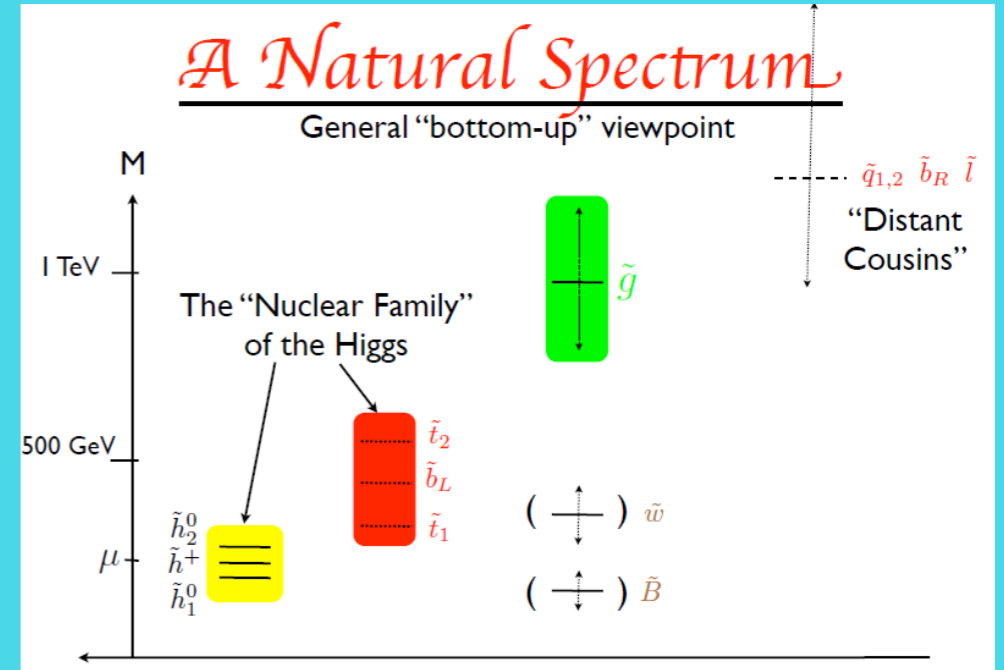
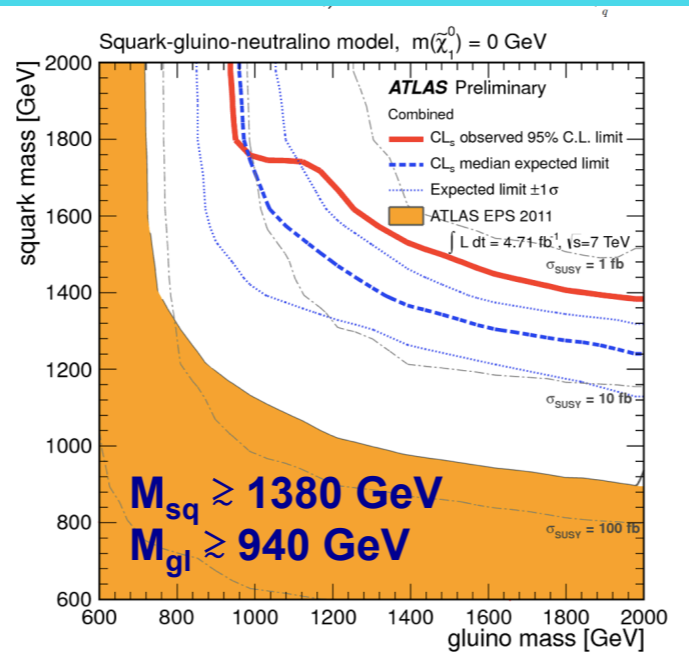
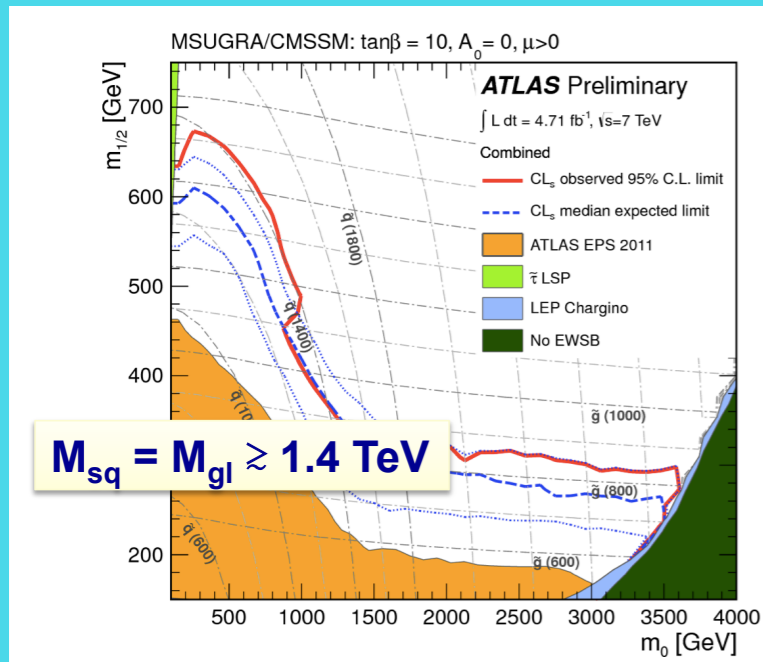
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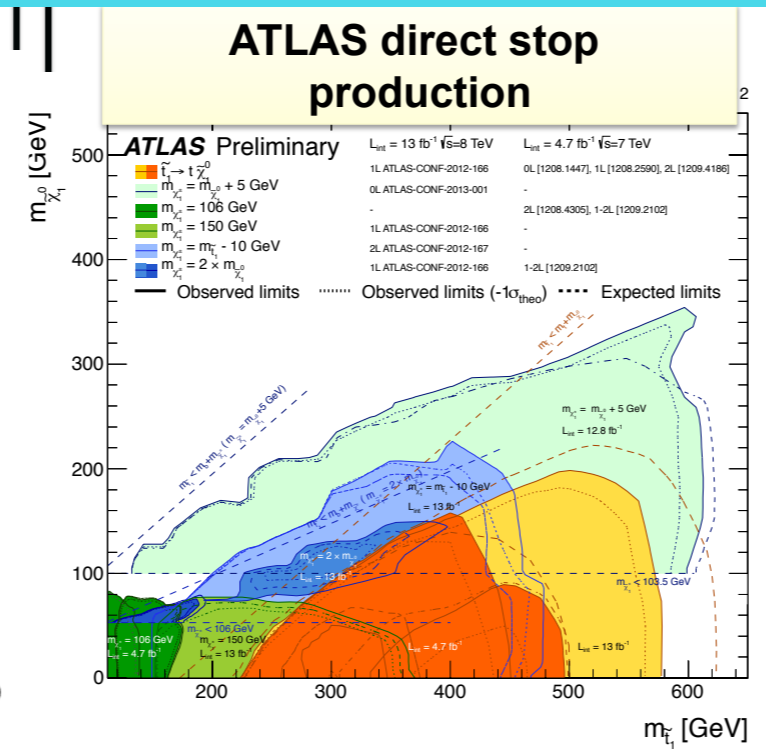
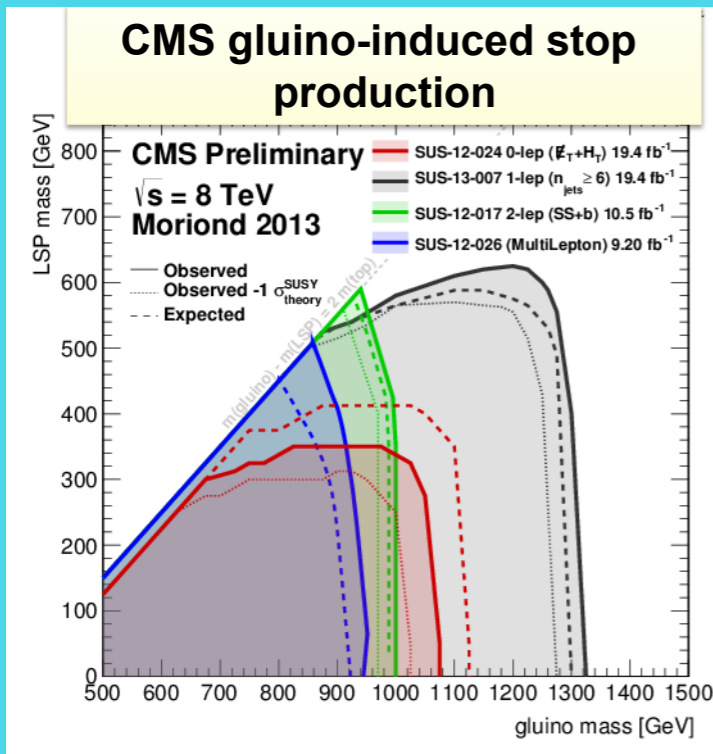
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Strongly interacting particles

Search for Supersymmetry @ LHC



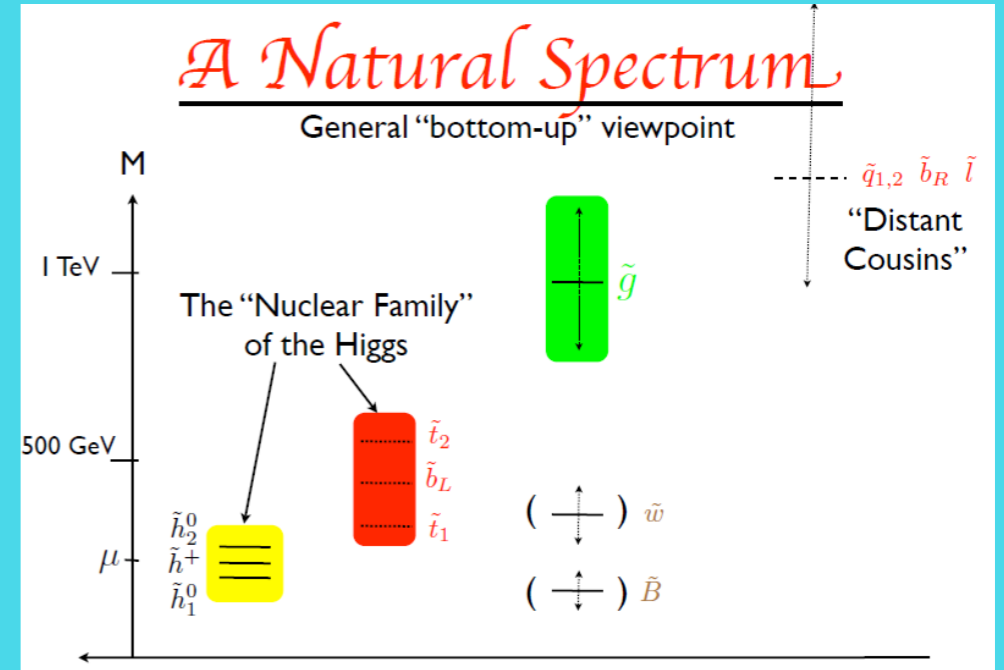
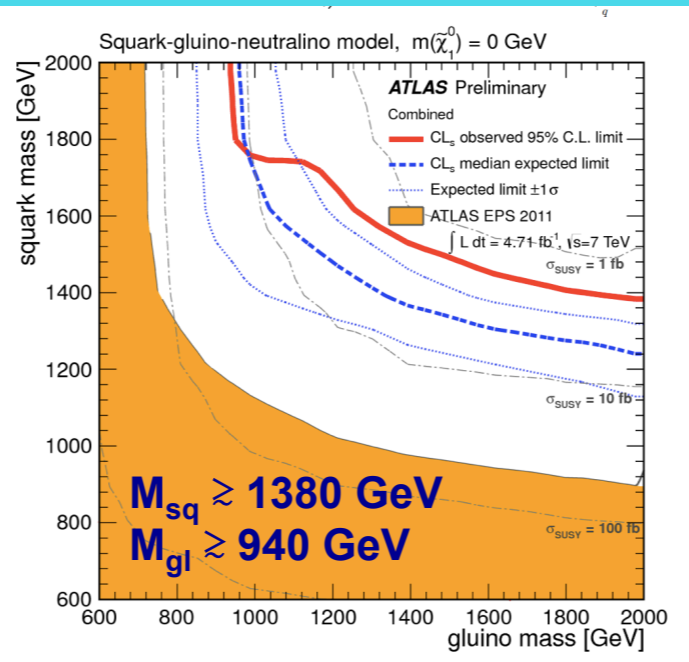
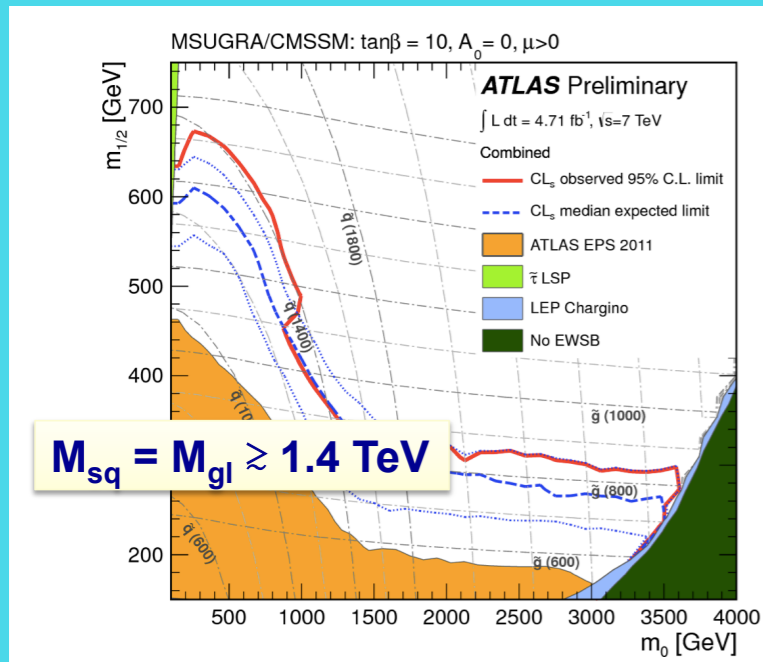
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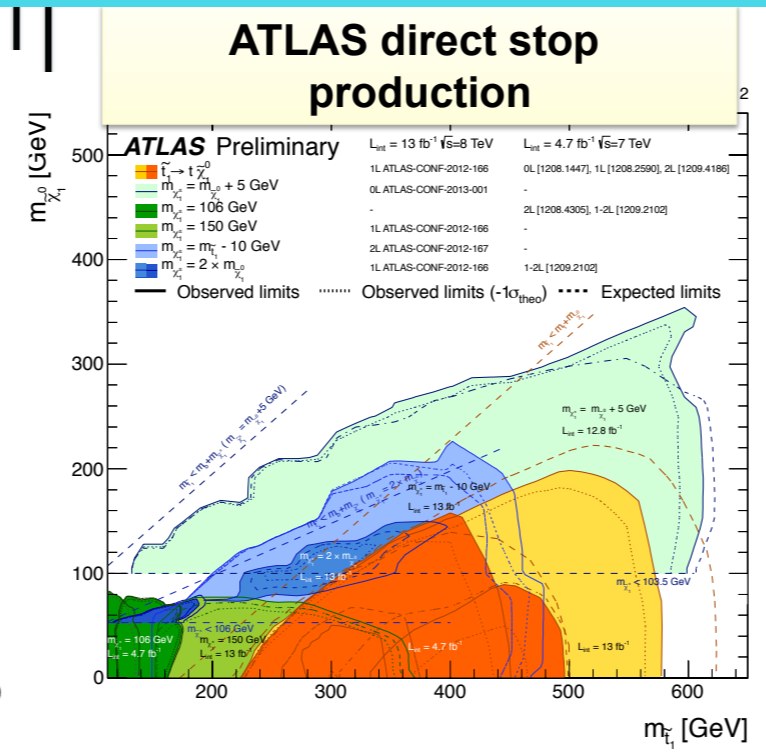
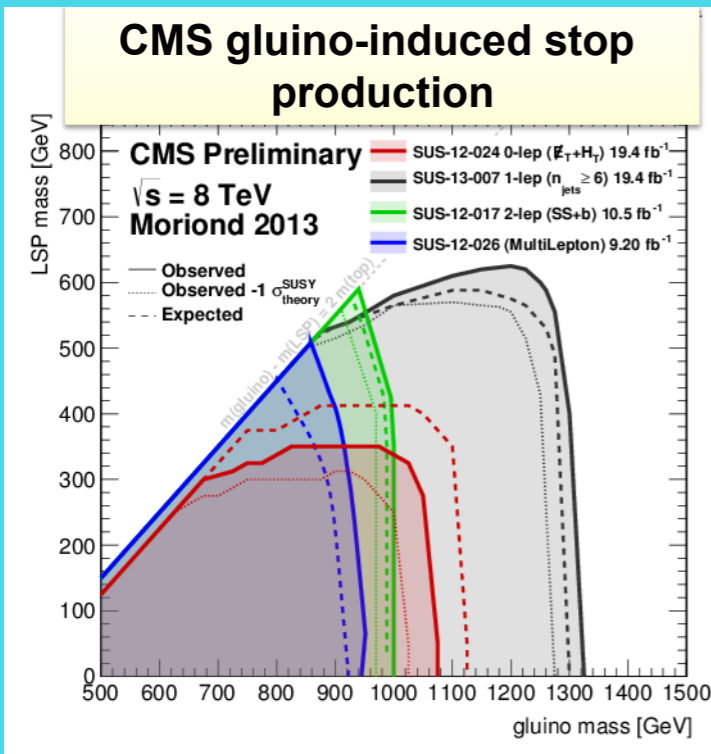
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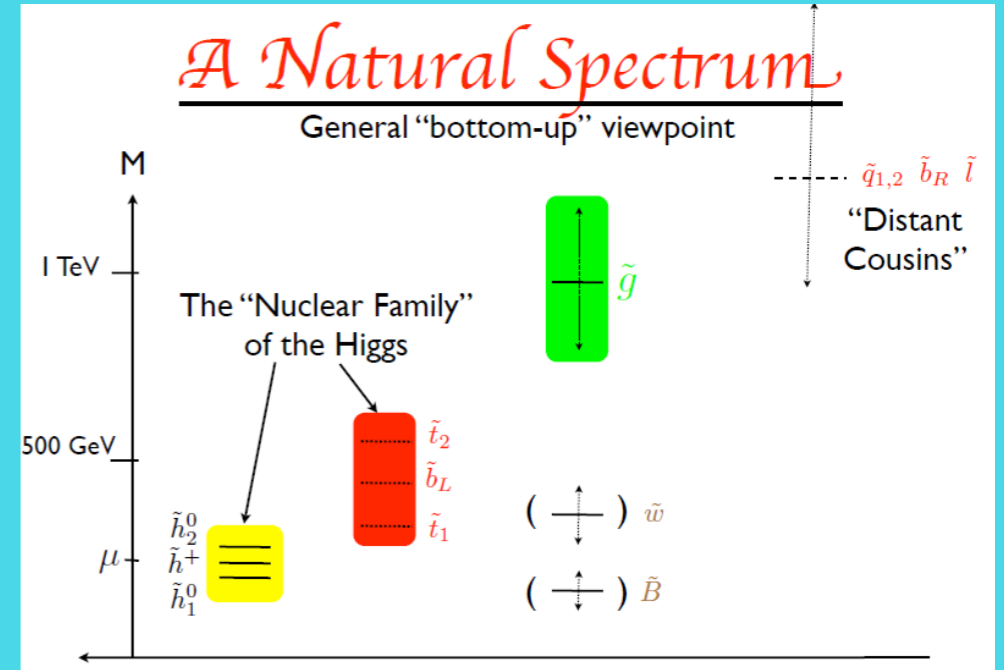
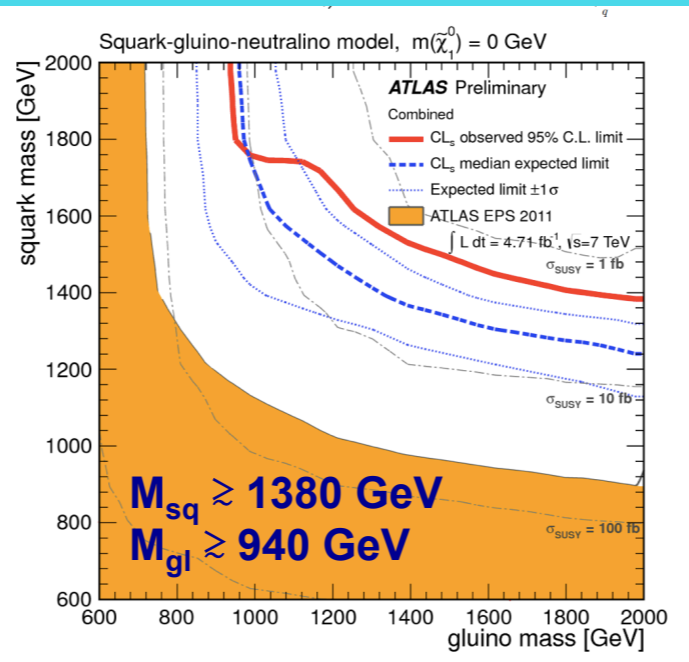
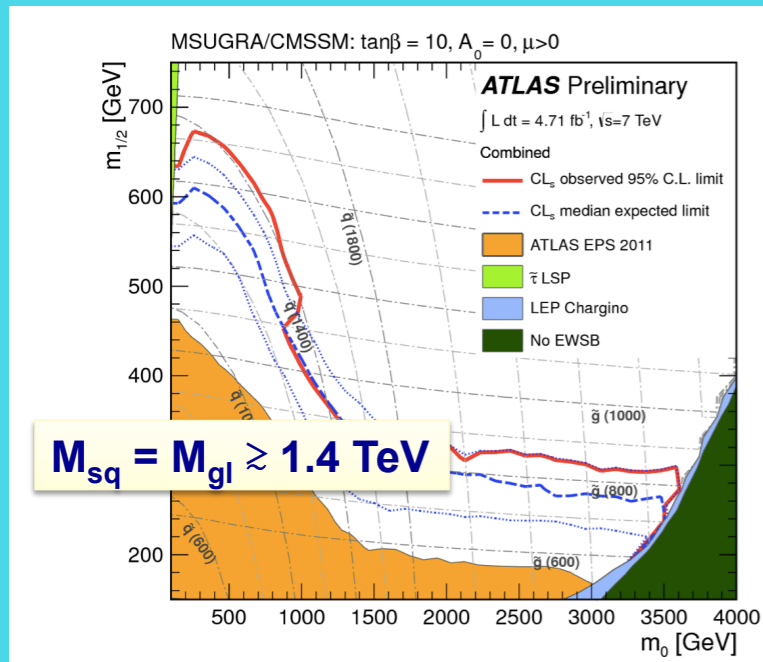


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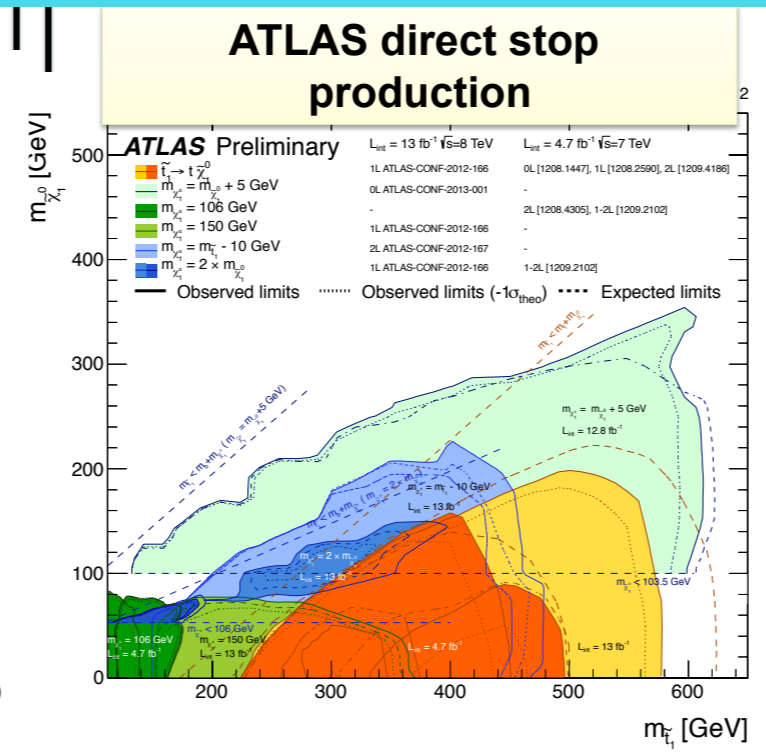
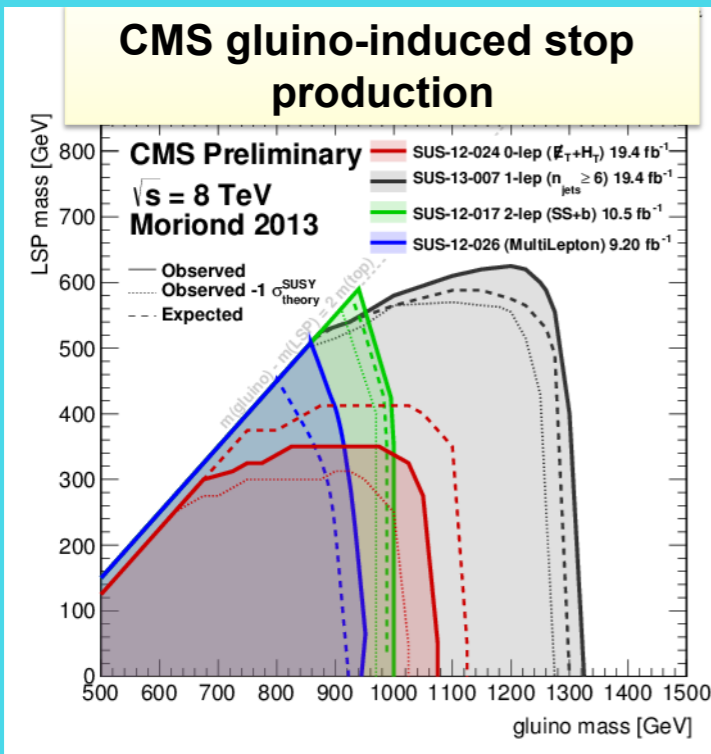
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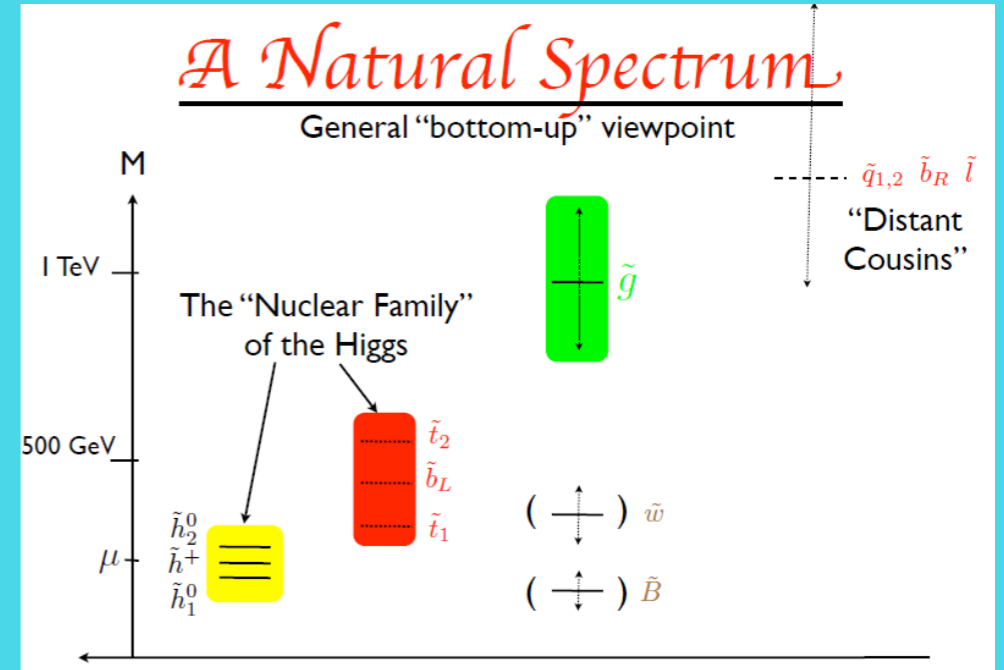
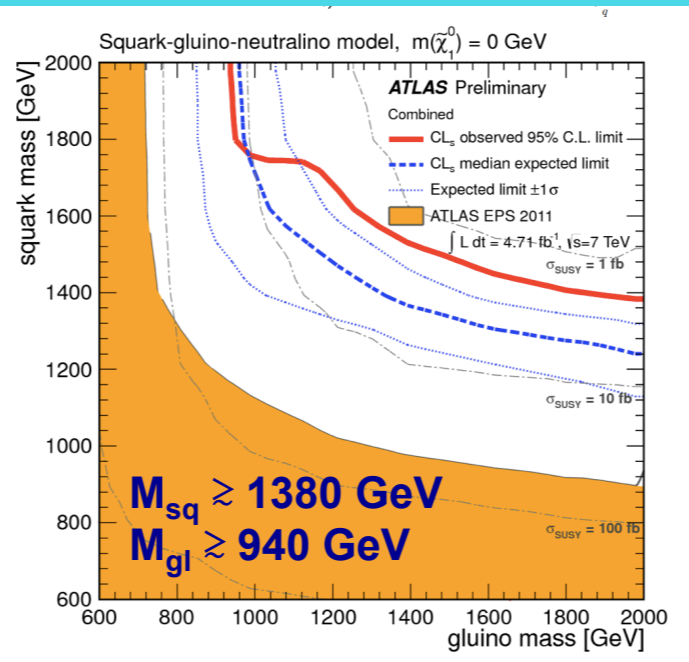
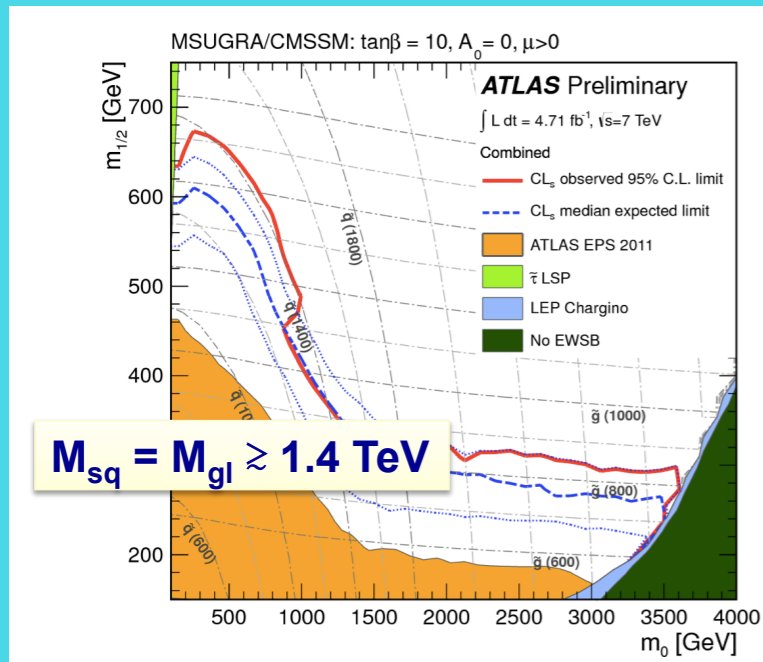


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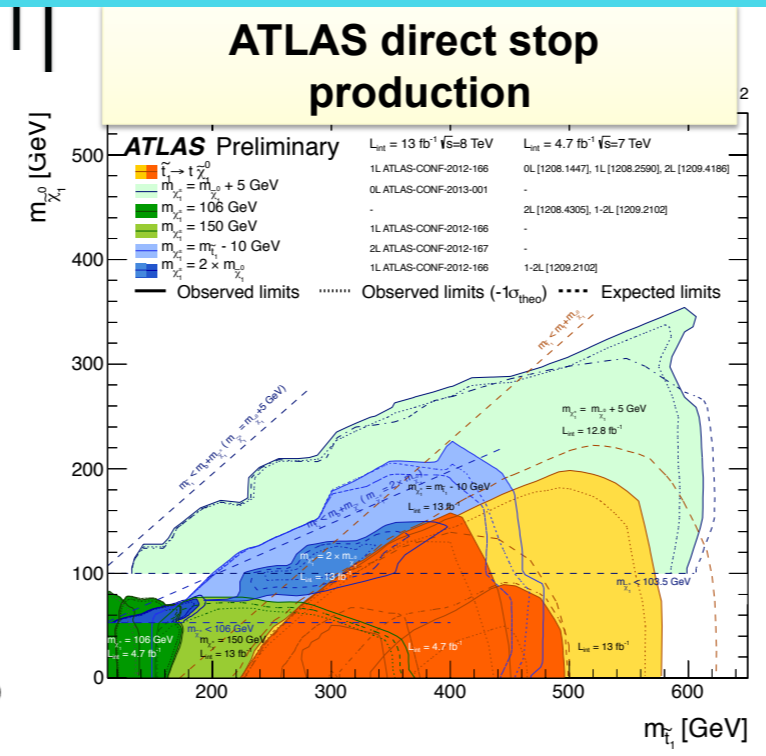
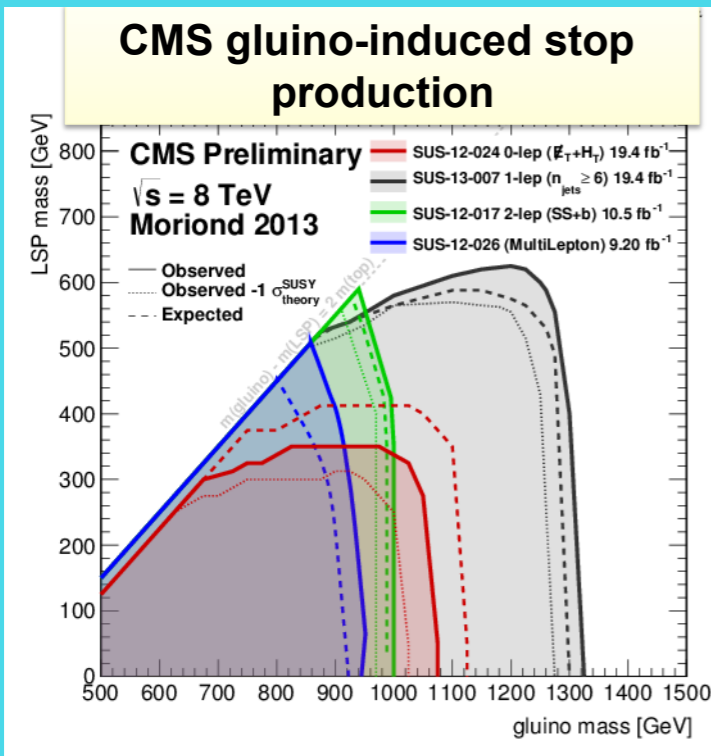
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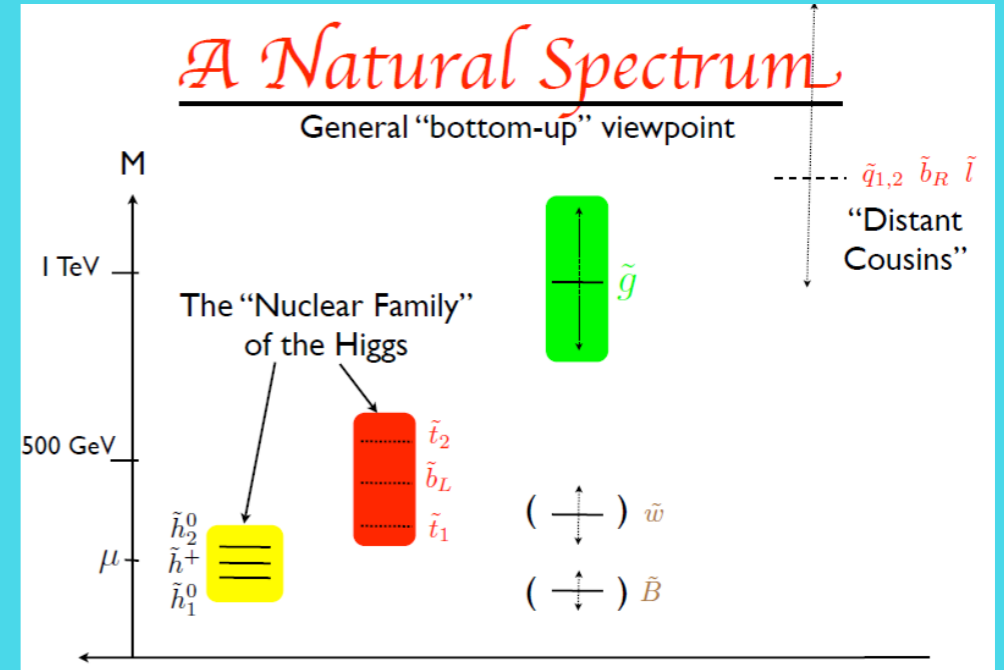
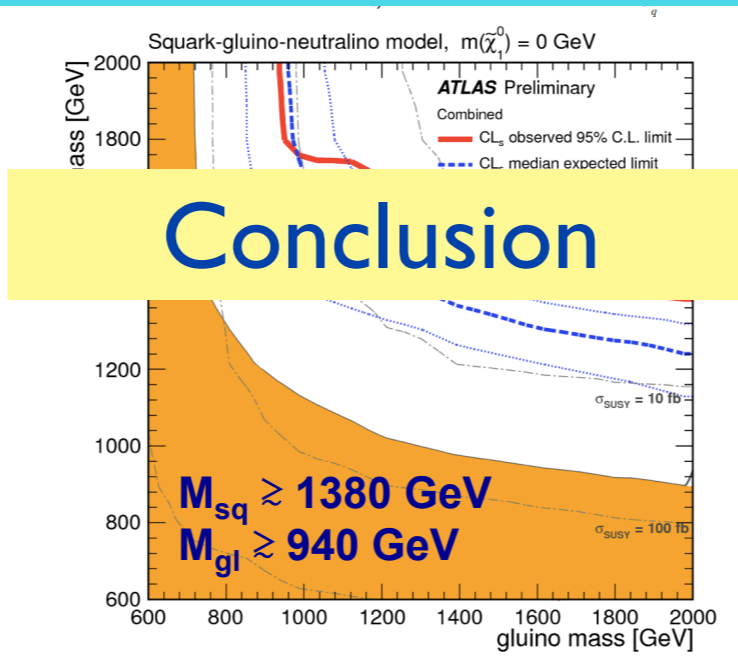
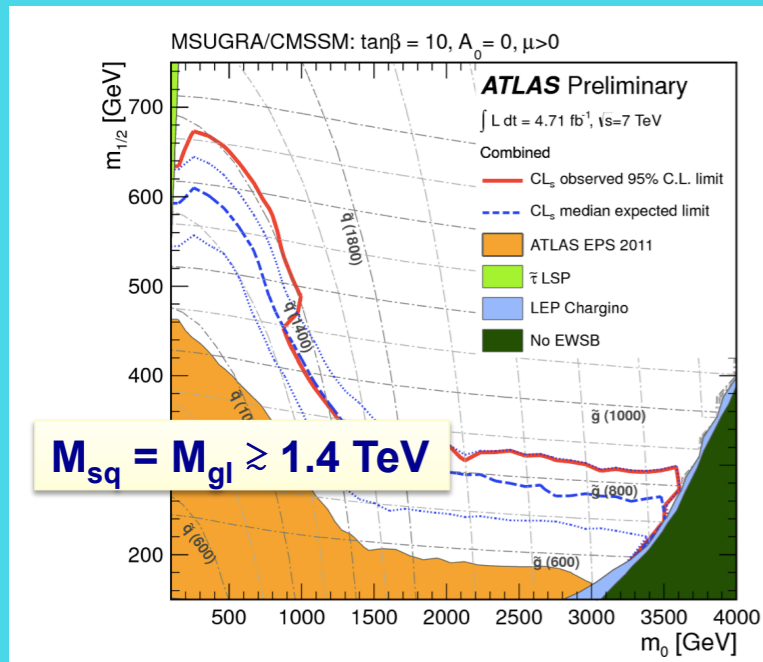
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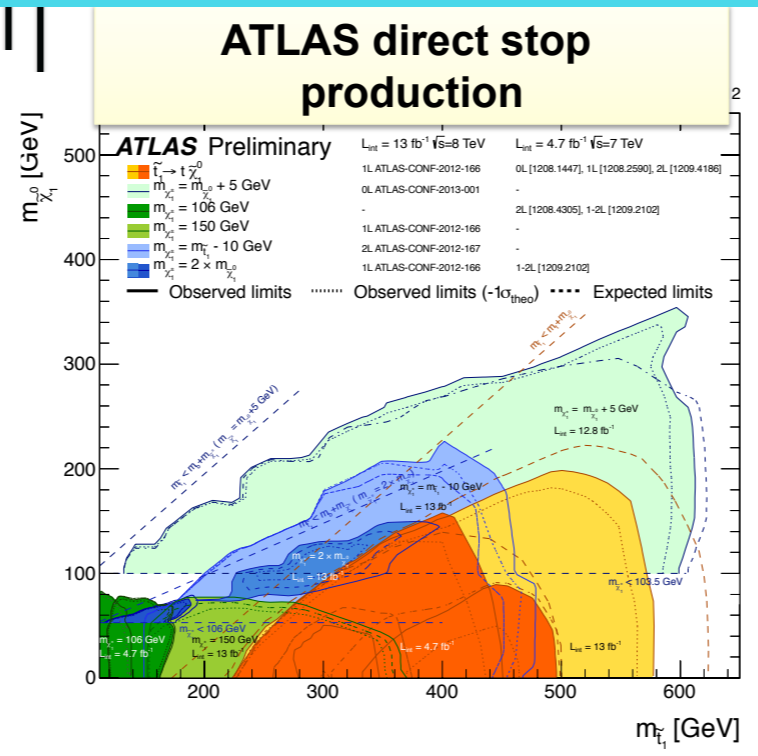
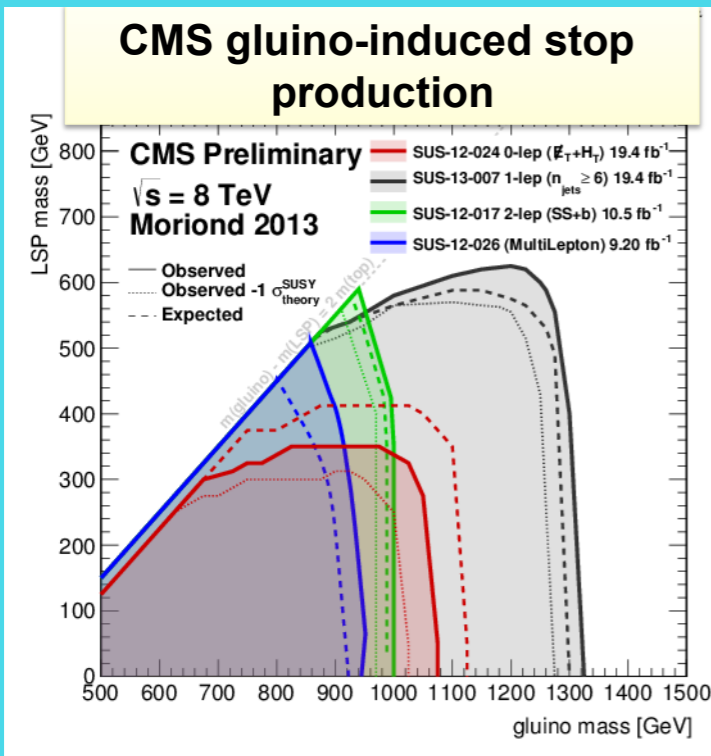
Looking in wrong place?

Still have not reached the the right mass interval?

Search for Supersymmetry @ LHC



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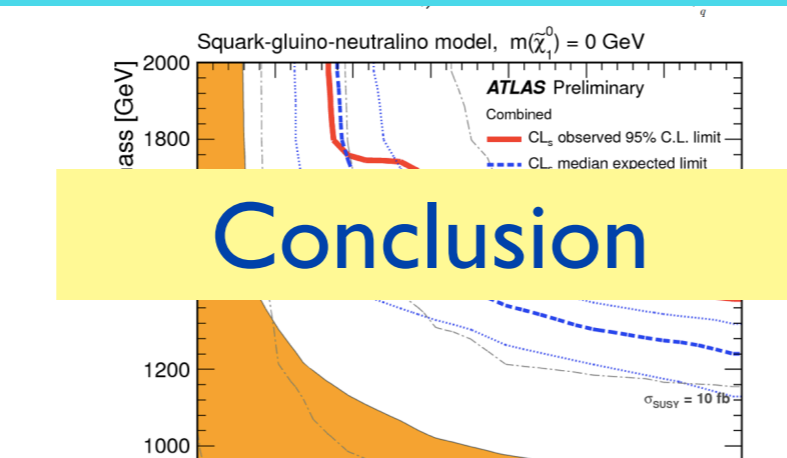
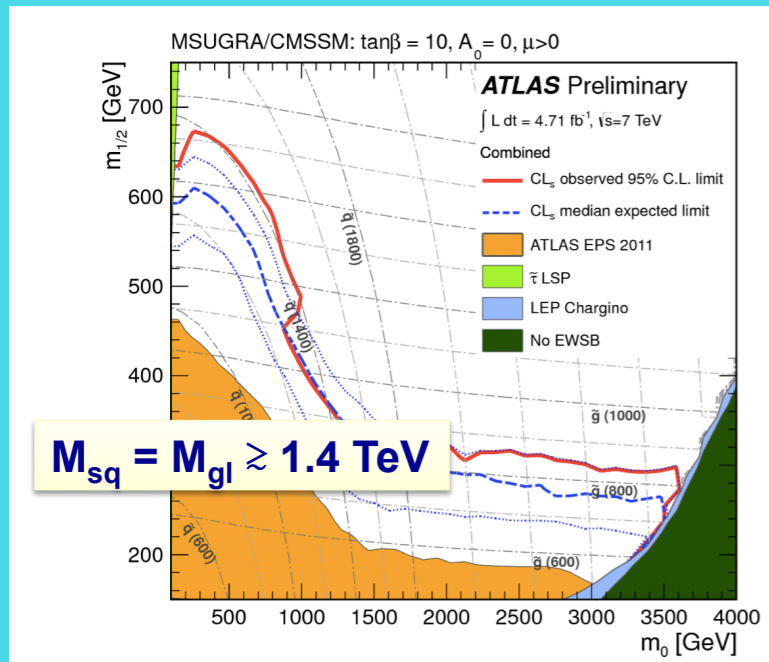
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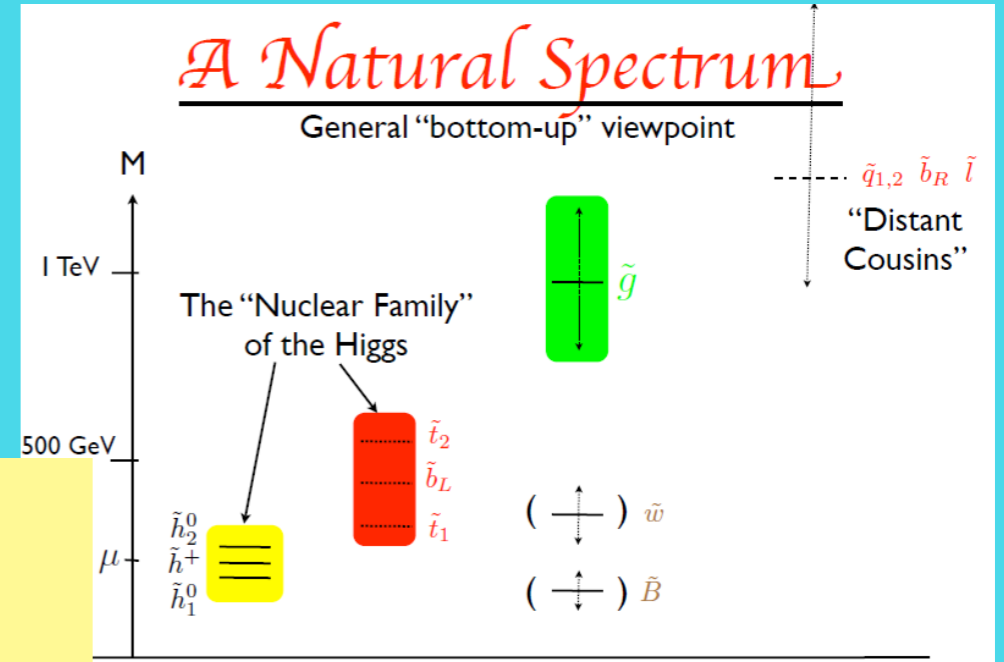
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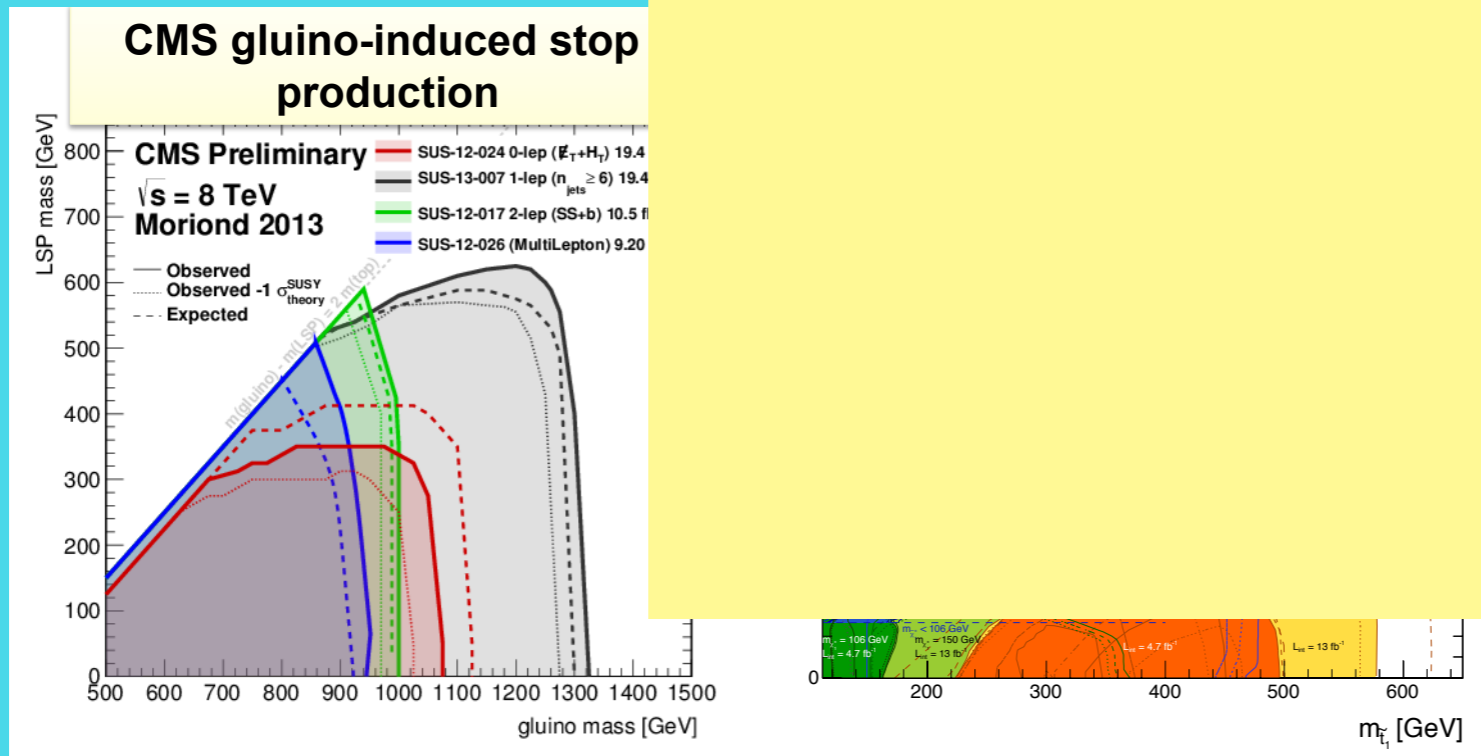


Conclusion

I. Still no sign of SUSY



Weakly interacting particles



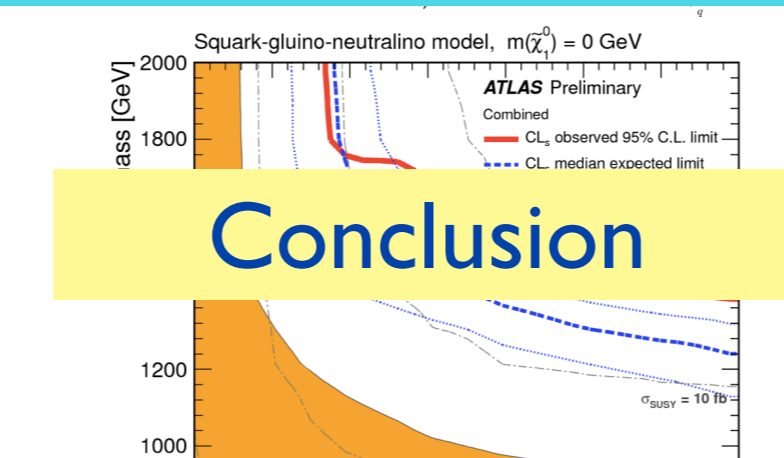
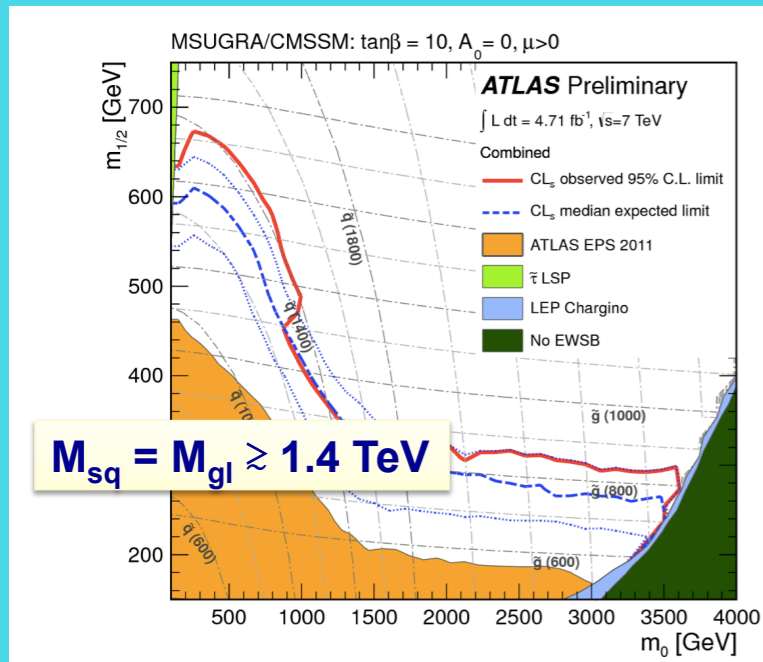
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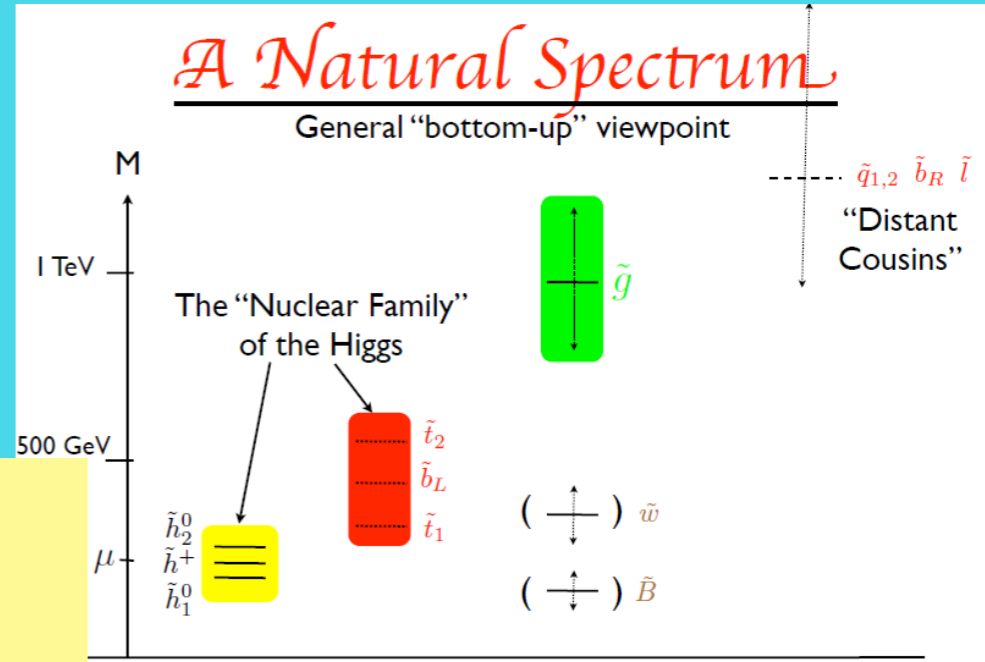
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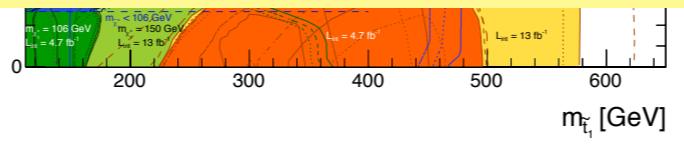
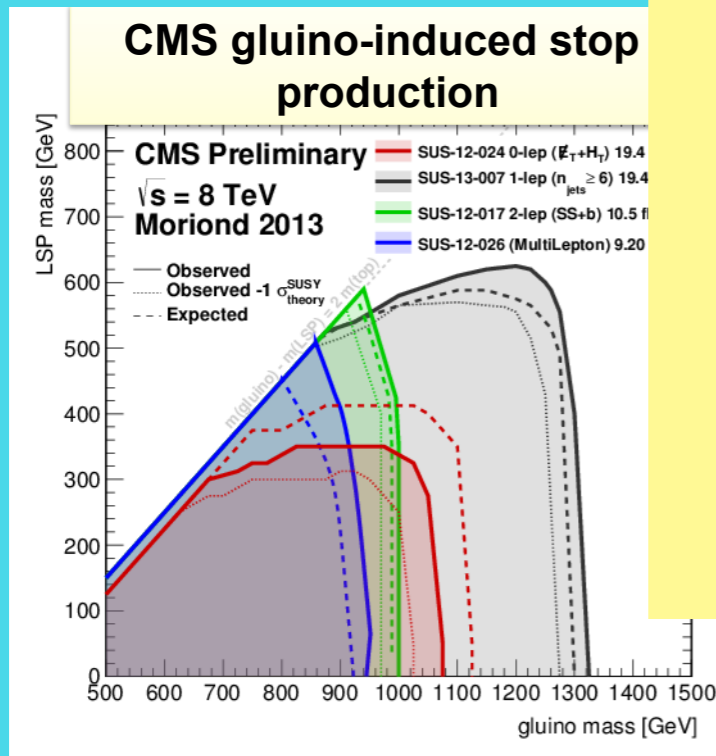


Conclusion

1. Still no sign of SUSY
 2. The obtained constraints are model dependent



Weakly interacting particles



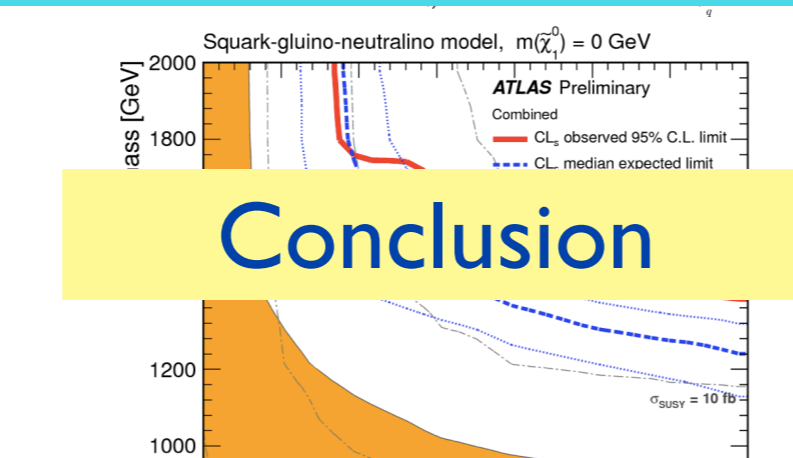
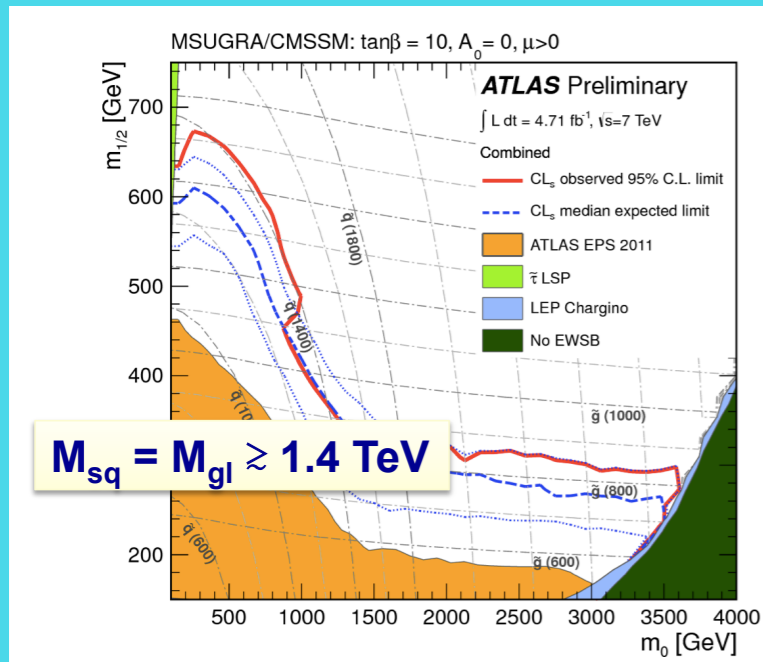
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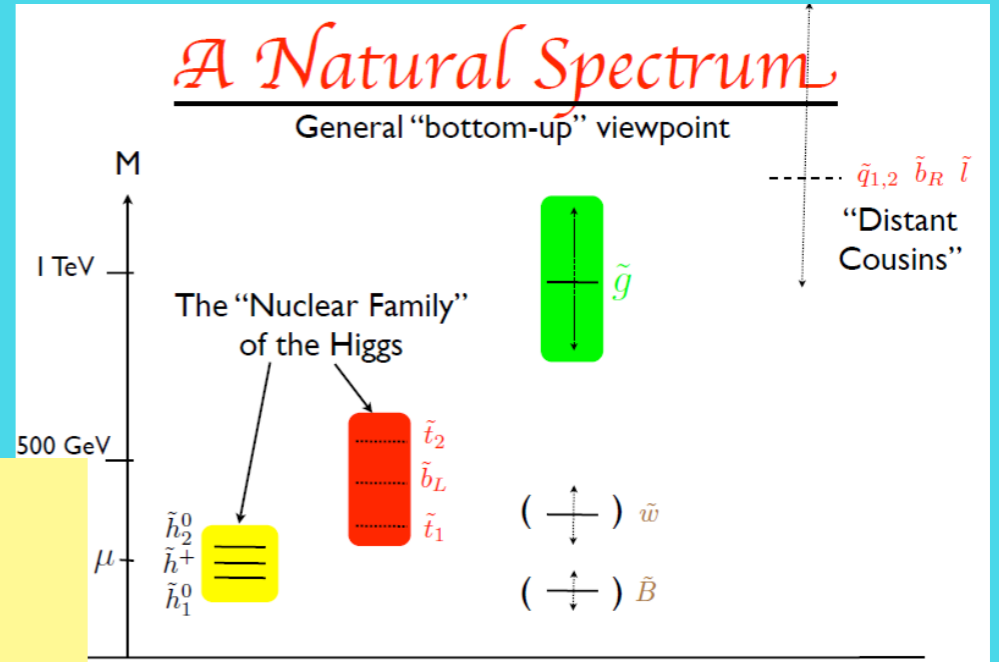
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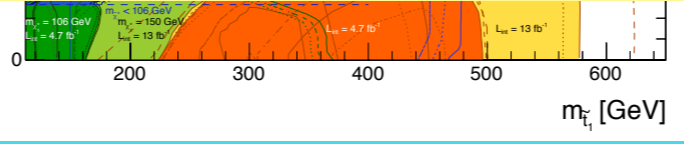
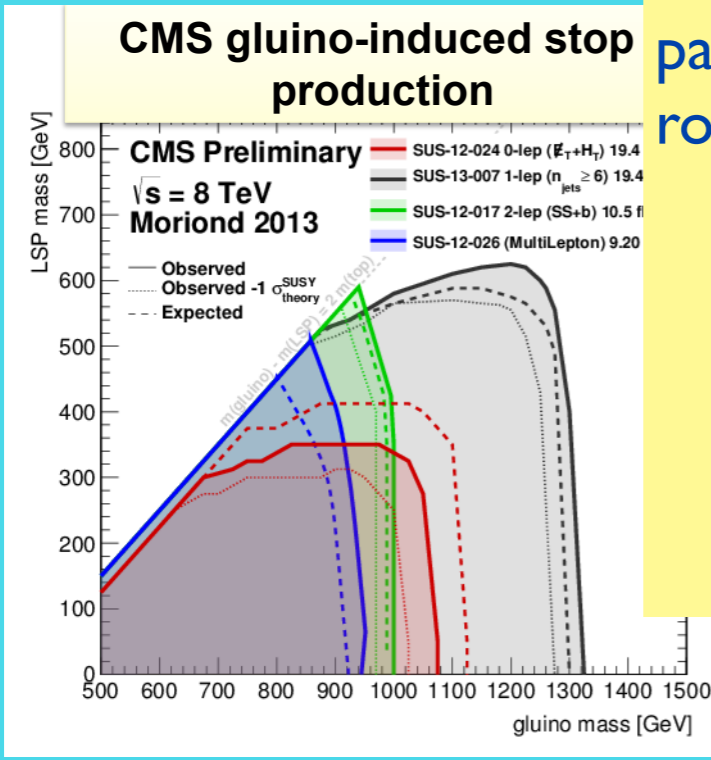


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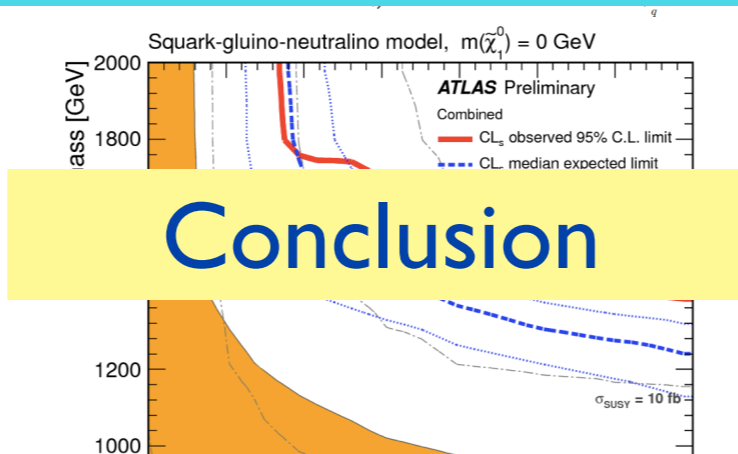
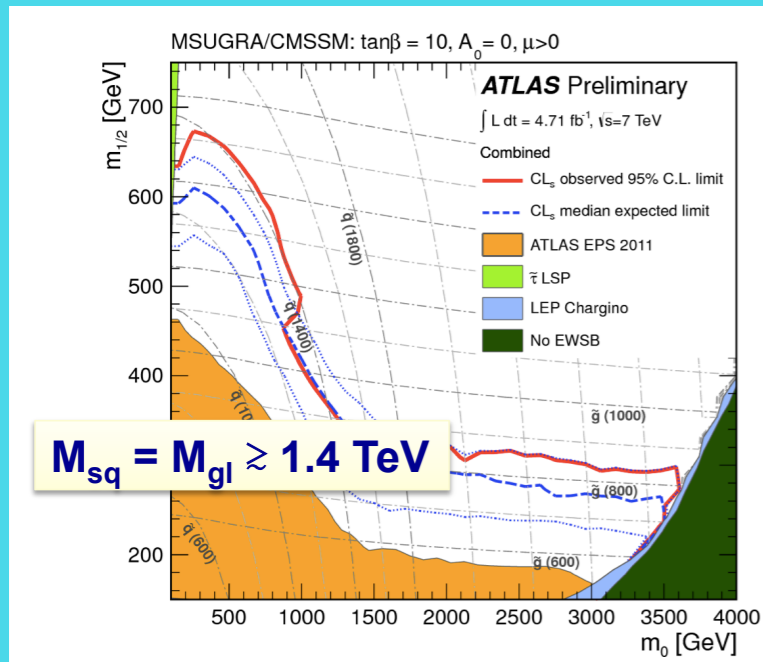
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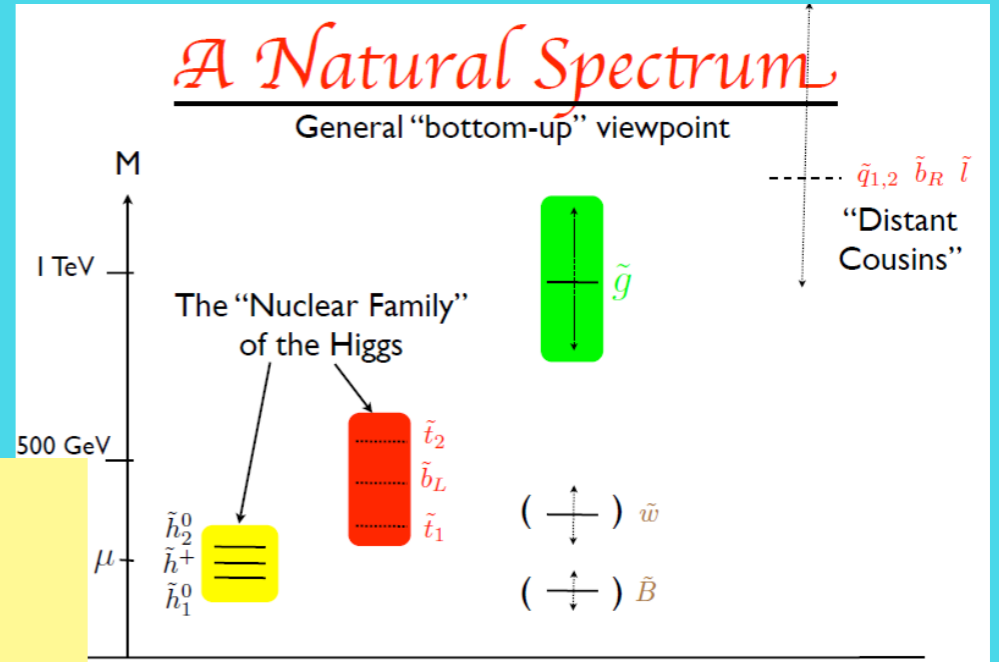
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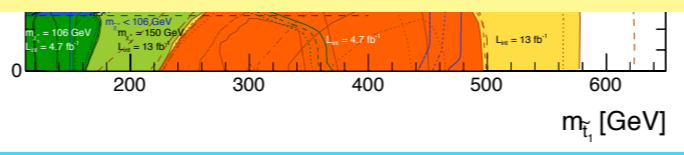
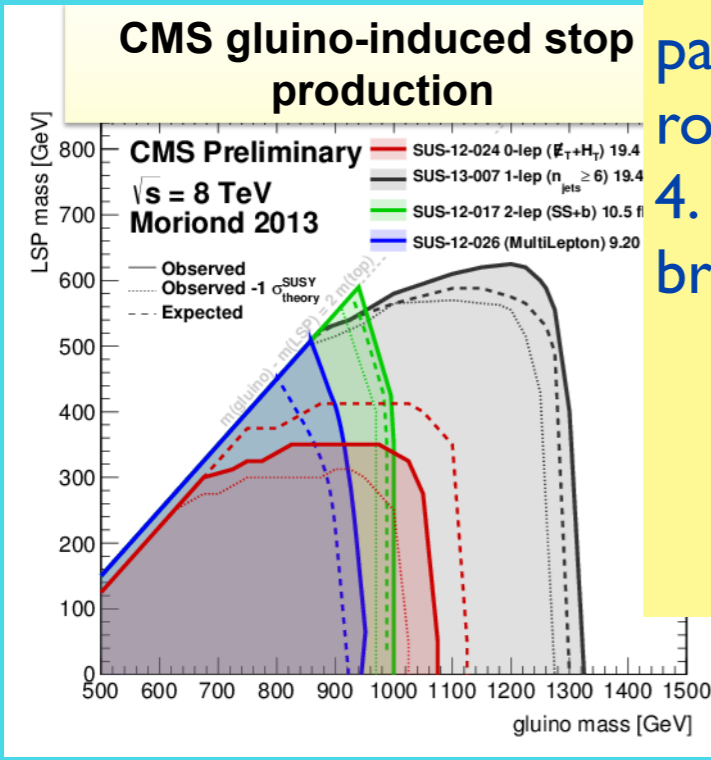


Conclusion

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2. The obtained constraints are model dependent
3. The models have many parameters and still there is large room for SUSY
4. It is possible that SUSY breaking is realised differently



Weakly interacting particles



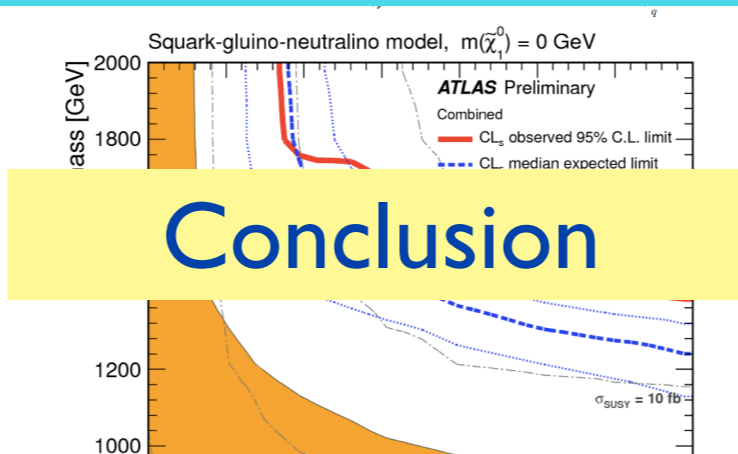
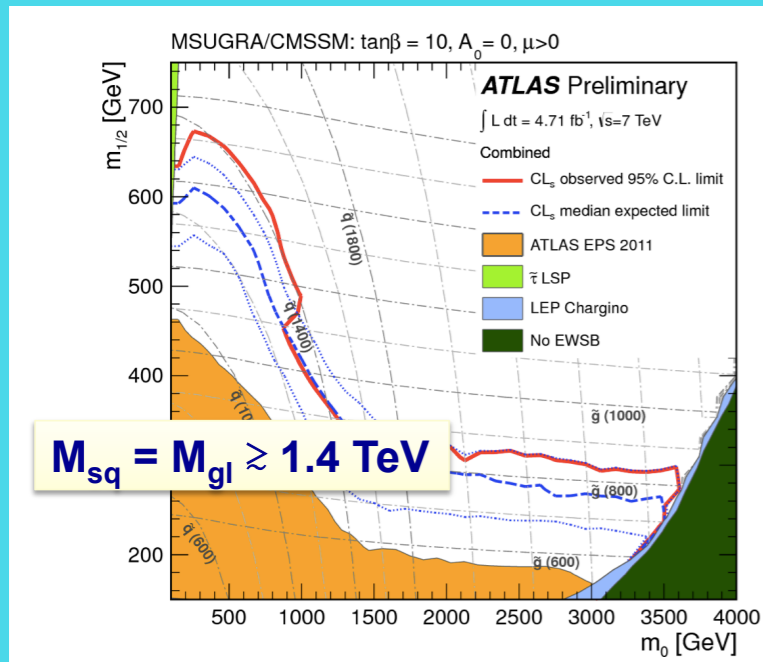
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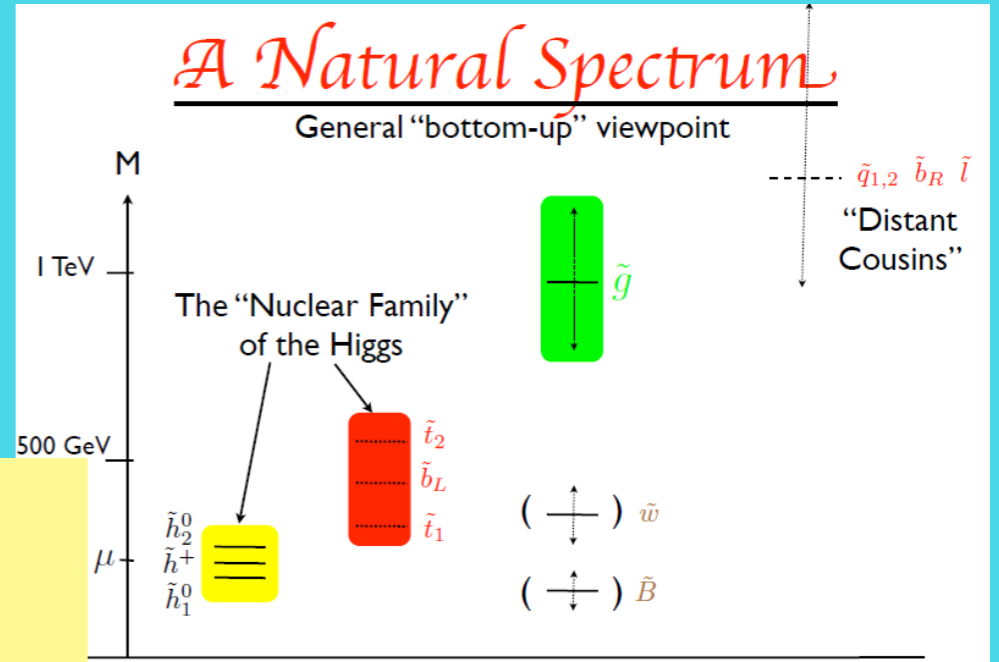
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Conclusion

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5. The future run of the accelerator at maximal energy of 14 TeV in 2016-2018 might be crucial for low energy SUSY

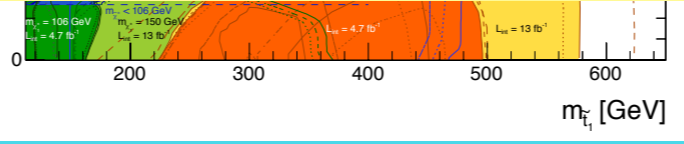
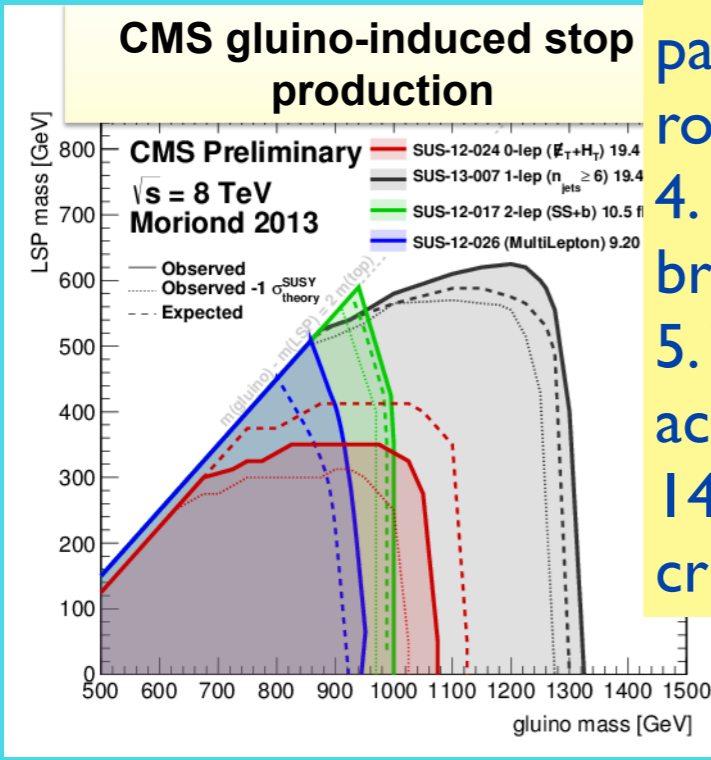


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Forward into the Future

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The research program for the coming years

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I. The study of the properties of the **new scalar particle** with maximal possible precision

Forward into the Future

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2. The search for any possible **deviations from the SM** indicating to existence of a new physics

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The fulfillment of this program might require the construction of a new **electron-positron** collider in addition to existing hadron collider.

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We live in exciting time and have a chance to unveil the mystery!