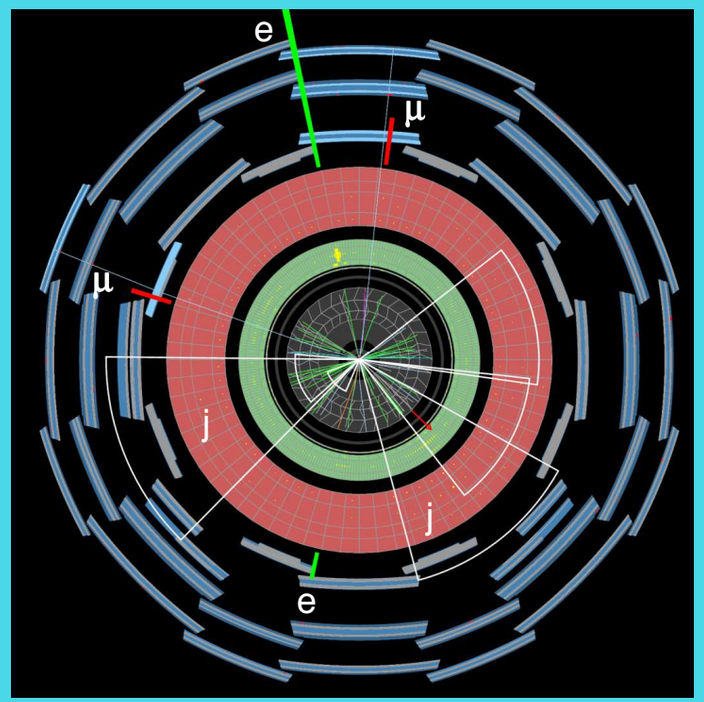
The Higgs boson is found: What is next?



Dmitry Kazakov

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

Moscow Institute of Physics and Technology

Round table «What Next».

4 March 2014

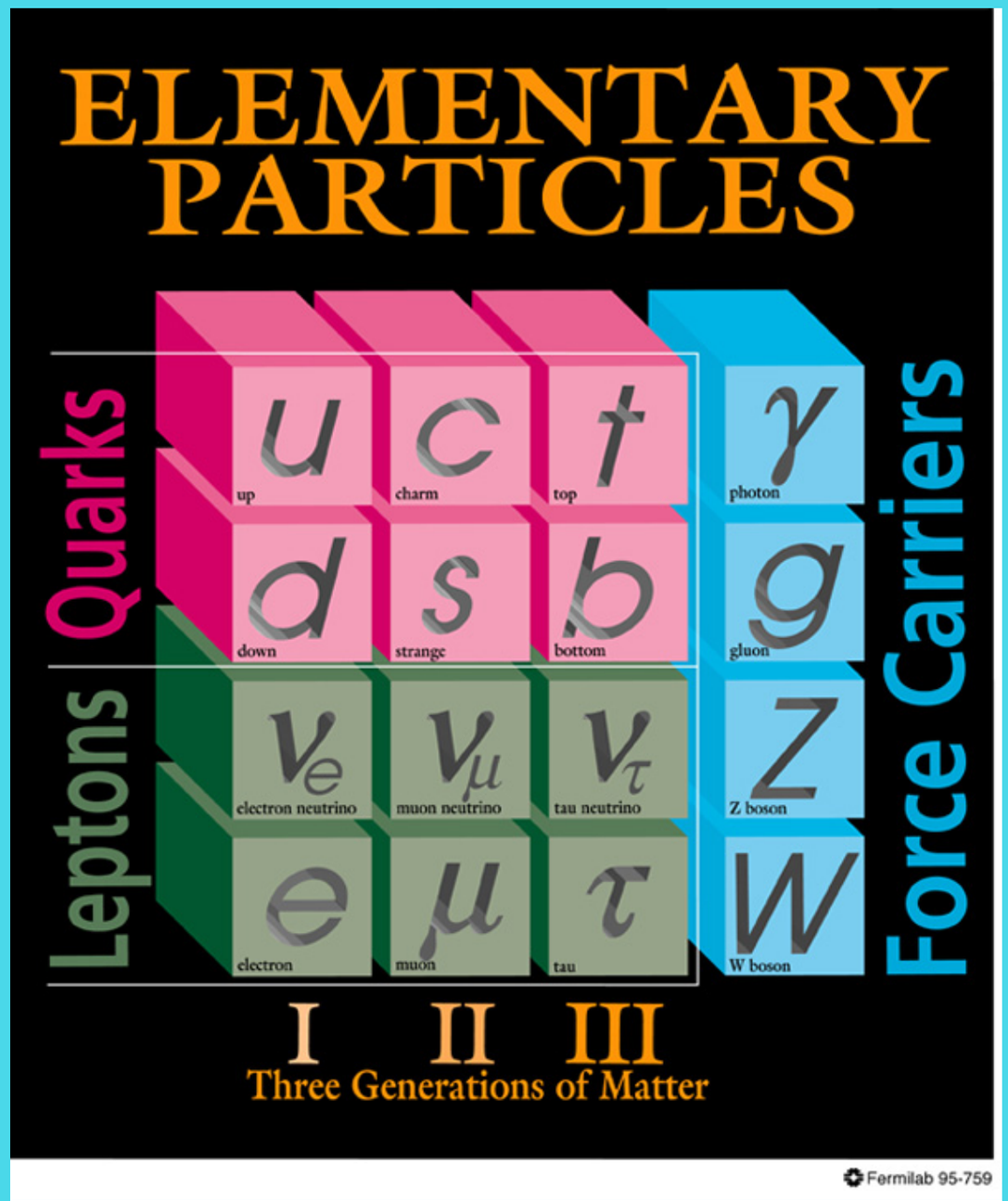
The Standard Model

SU(3)

SU(2)

U(1)

Particles



Forces

U(1) Electromagnetic

Strong

Weak

The Higgs boson

Gravity

The Standard Model

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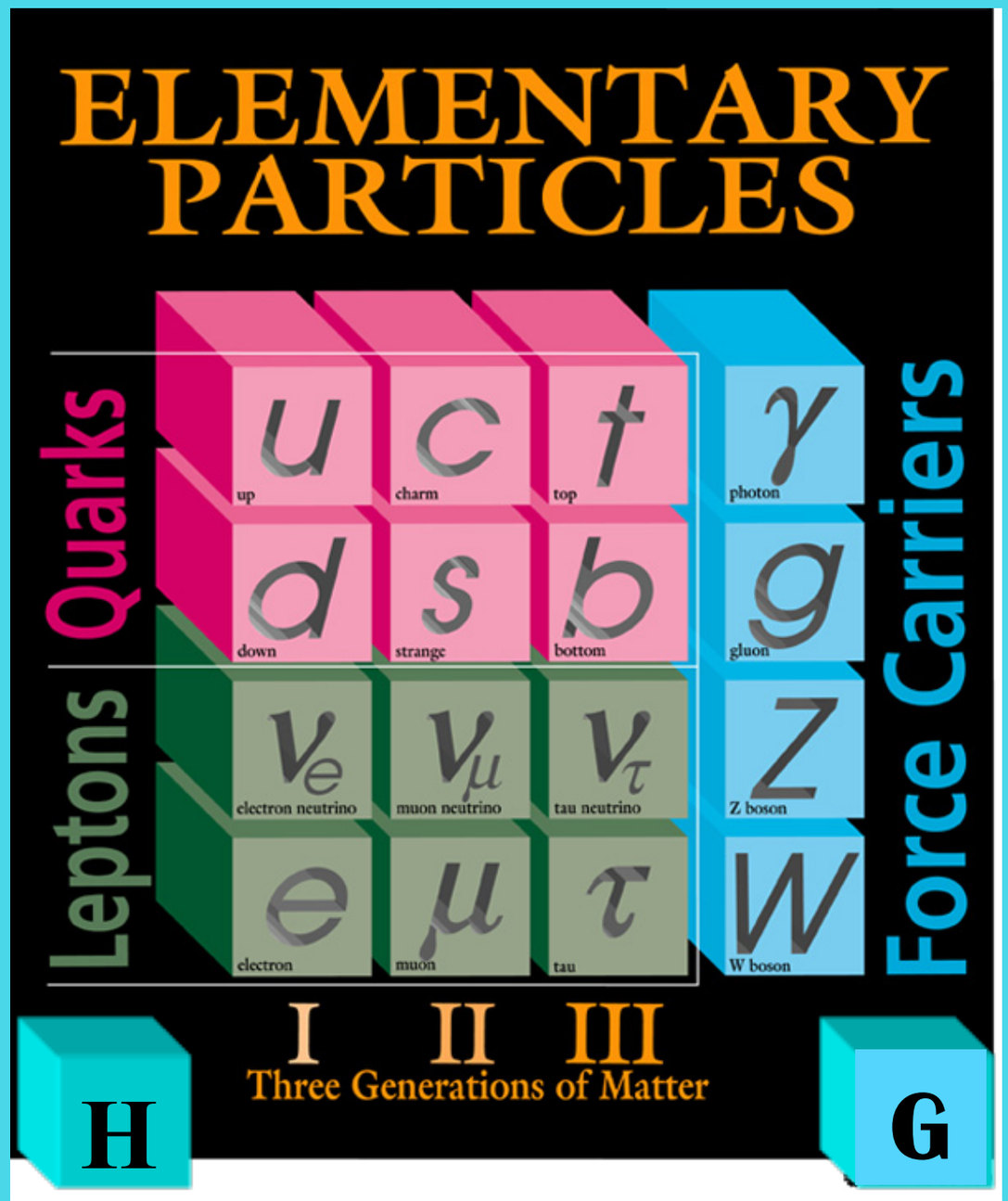

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- This is the beginning of a new research program with decades to go.

The Standard Model of Fundamental Interactions

Higgs Sector

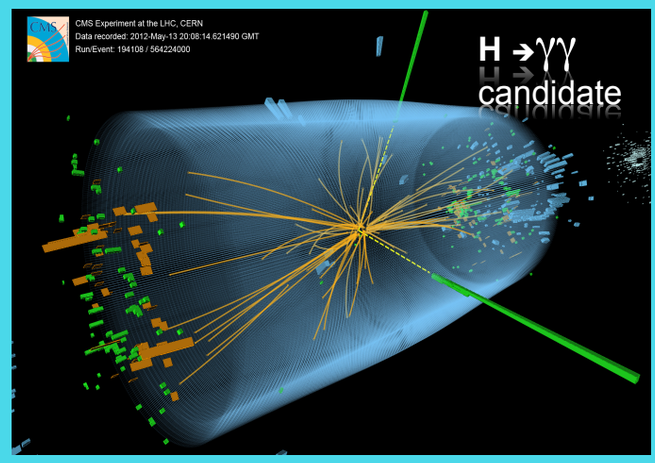
Neutrino Sector

Flavour Sector

Dark Matter

New particles and Interactions

The Higgs Sector



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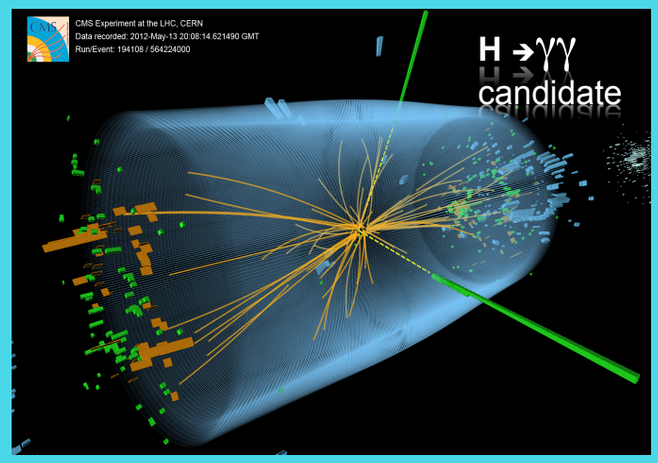

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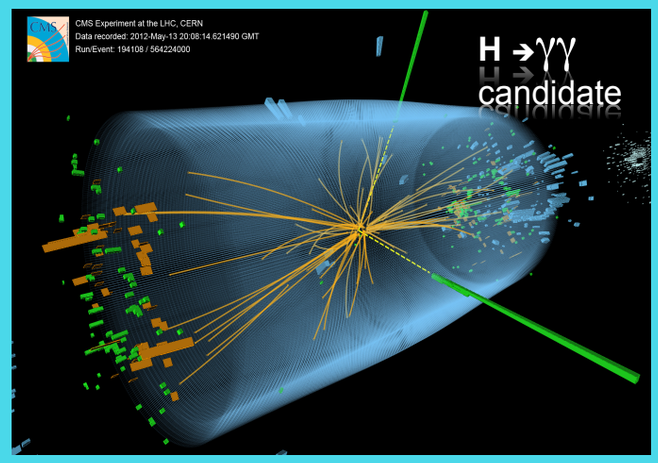

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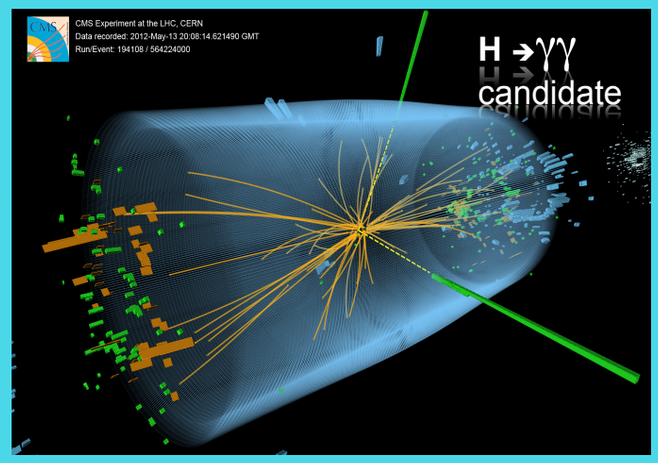

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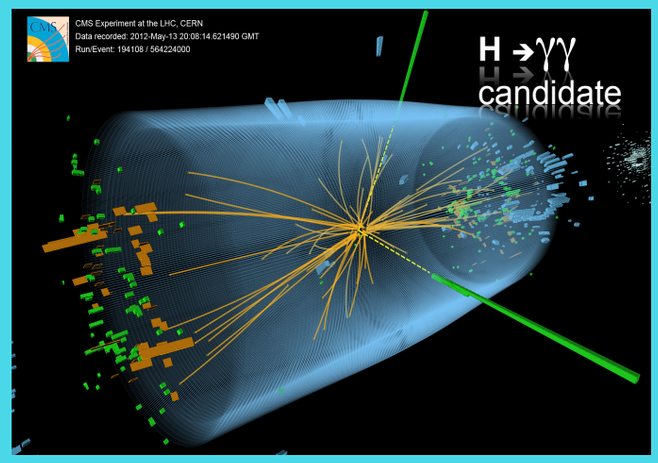

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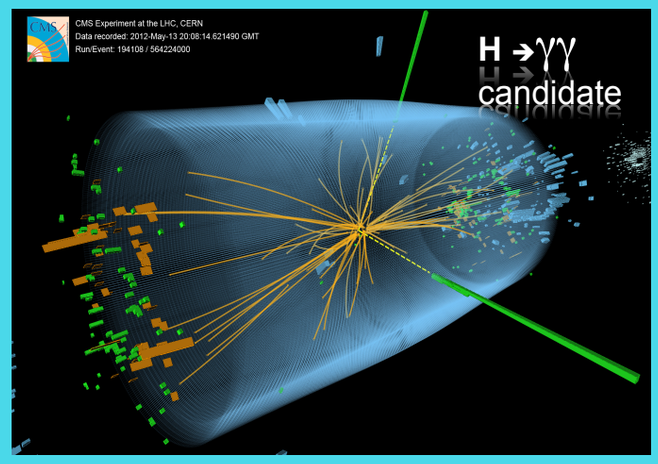

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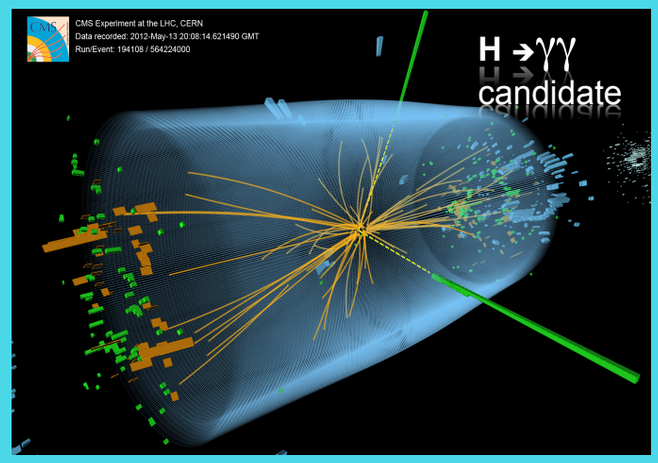

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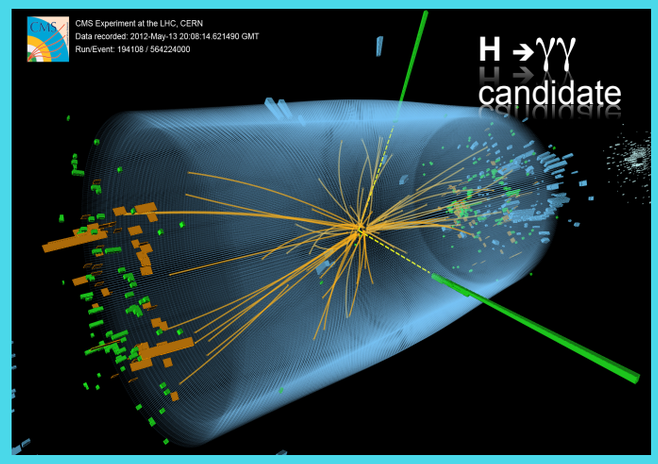

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We have got the confirmation that particles obtain their masses as a result of interaction with the Brout-Englert-Higgs field (whatever model the Higgs boson belongs to)

The Higgs Sector: Alternatives

Model	Particle content
SM	h CP-even
2HDM/MSSM	h,H CP-even A CP-odd $H^{\pm}$
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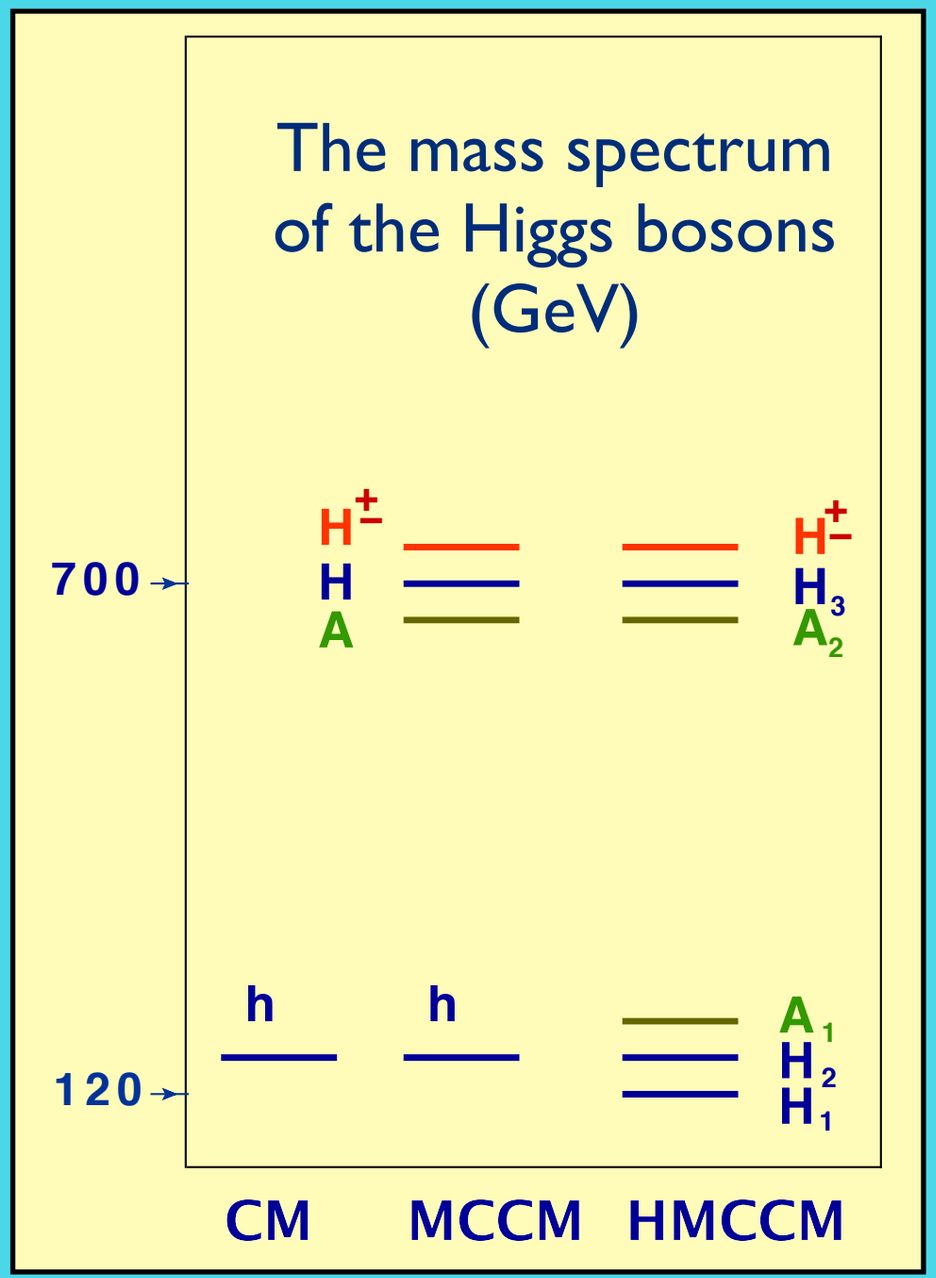

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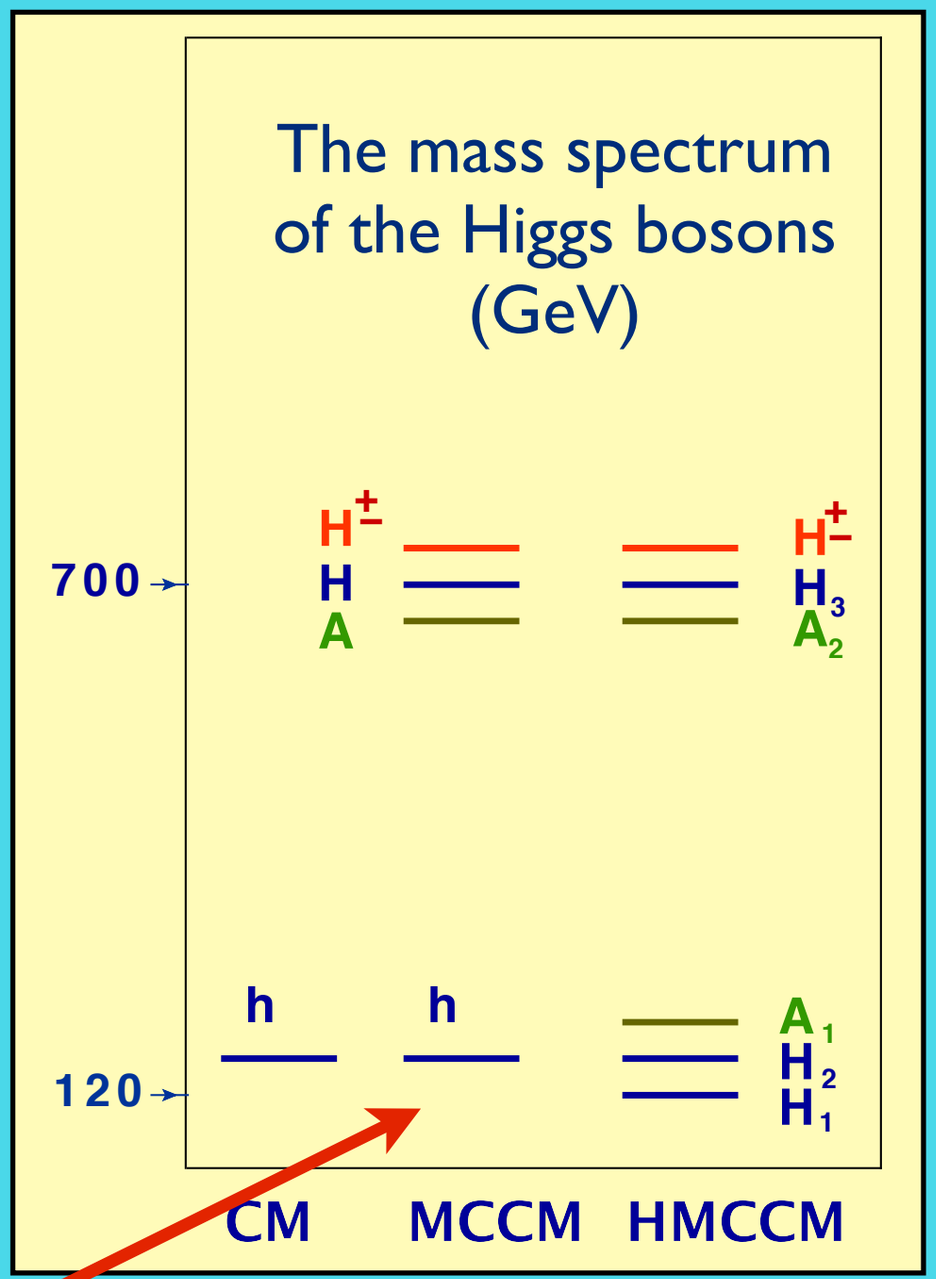

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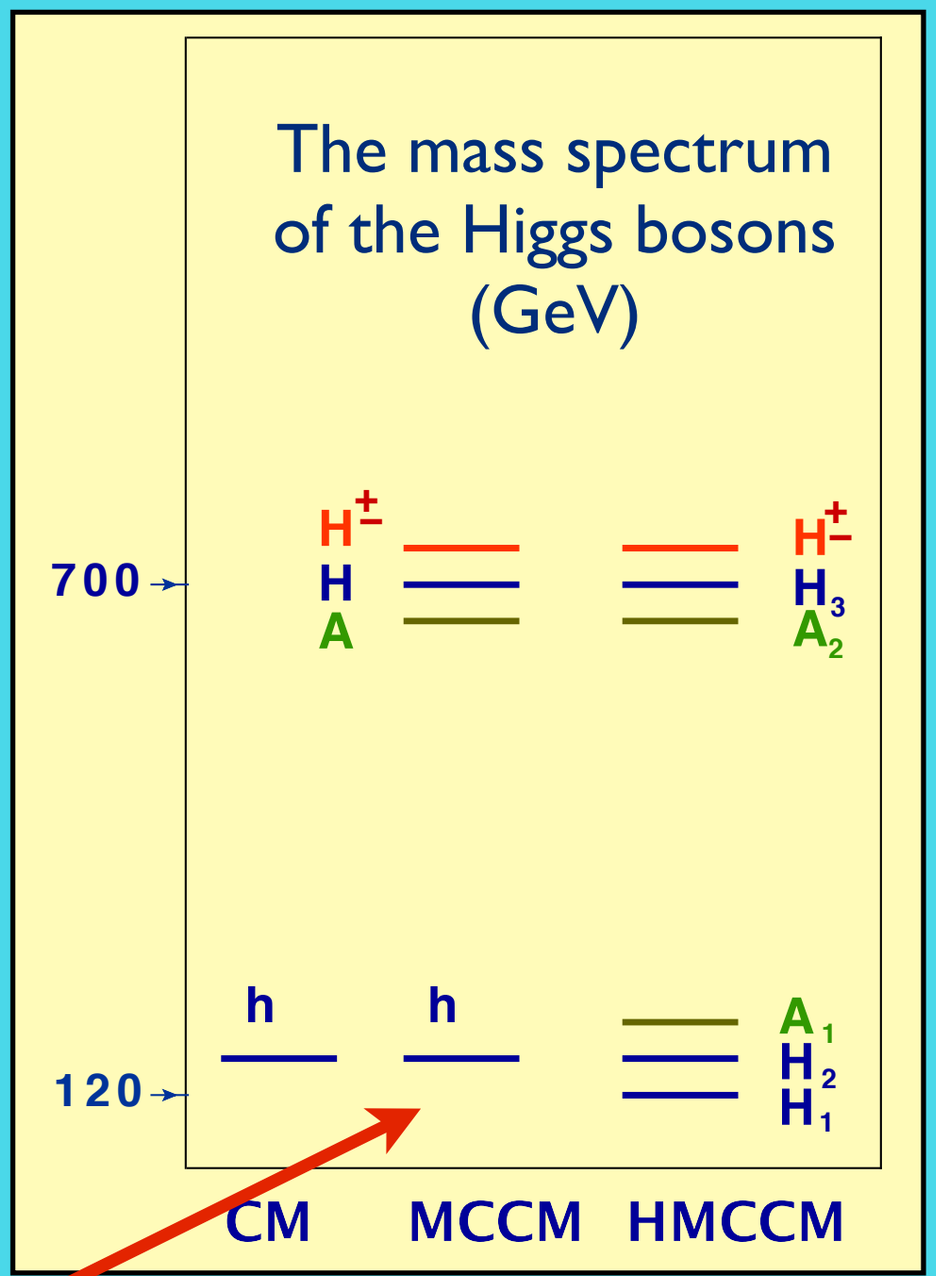

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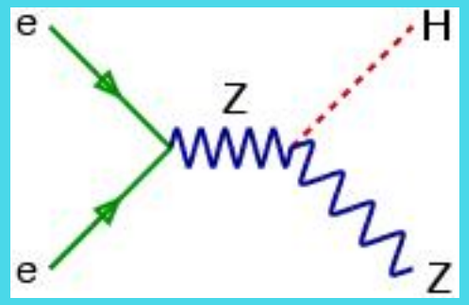
One has to check the presence or absence of heavy Higgs bosons

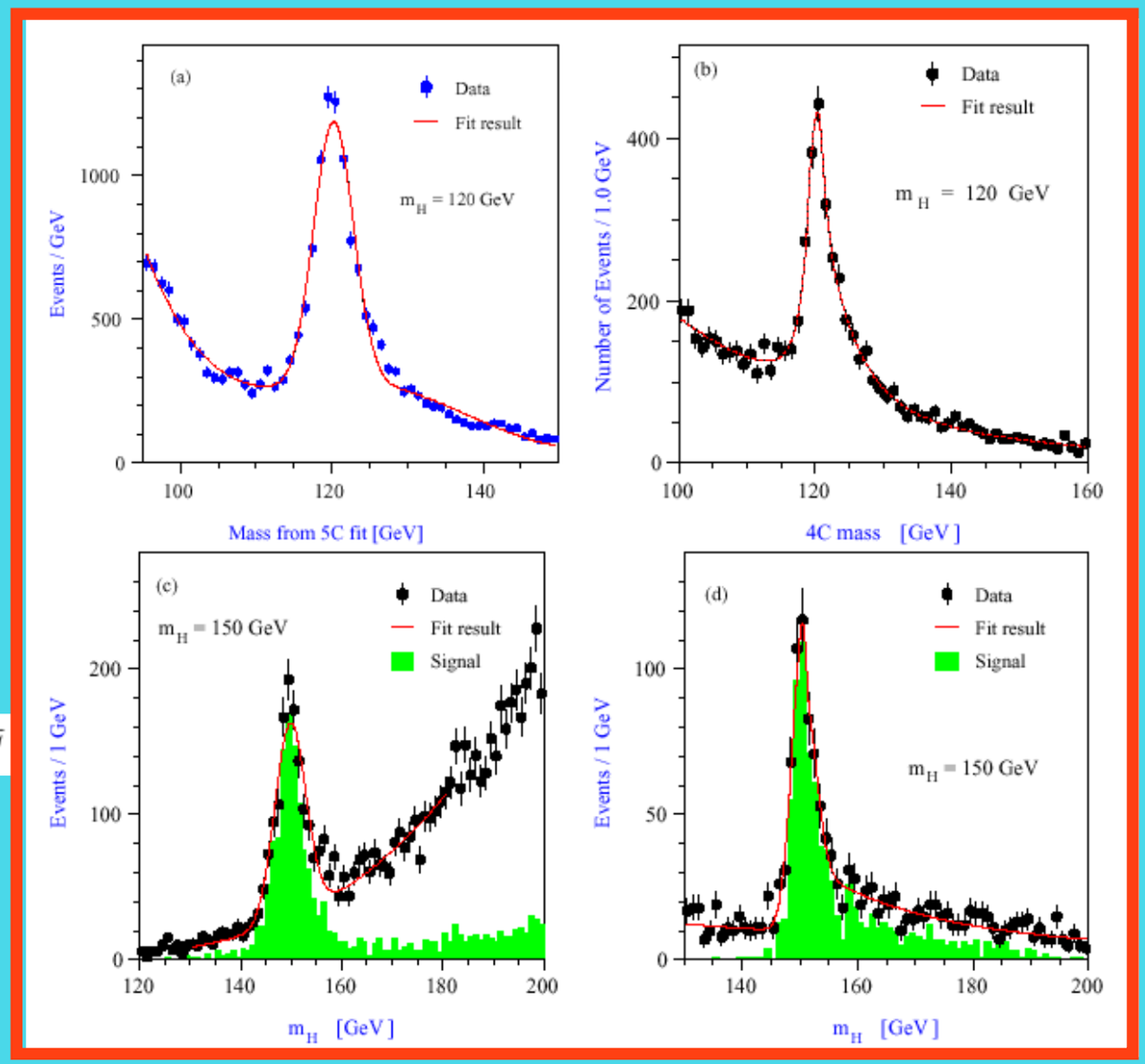
Precision Physics of the Higgs bosons



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

ee -> HZ diff. decay channels

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



$\rightarrow \; q\bar{q}\ell^+\ell^-$

$\Delta m_H =$ 40 MeV

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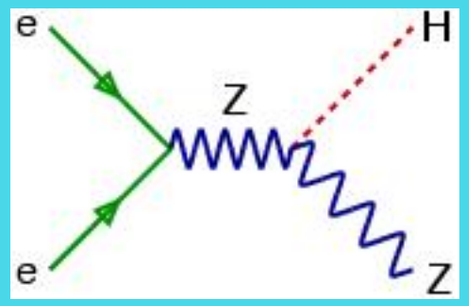

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Int Linear Collider

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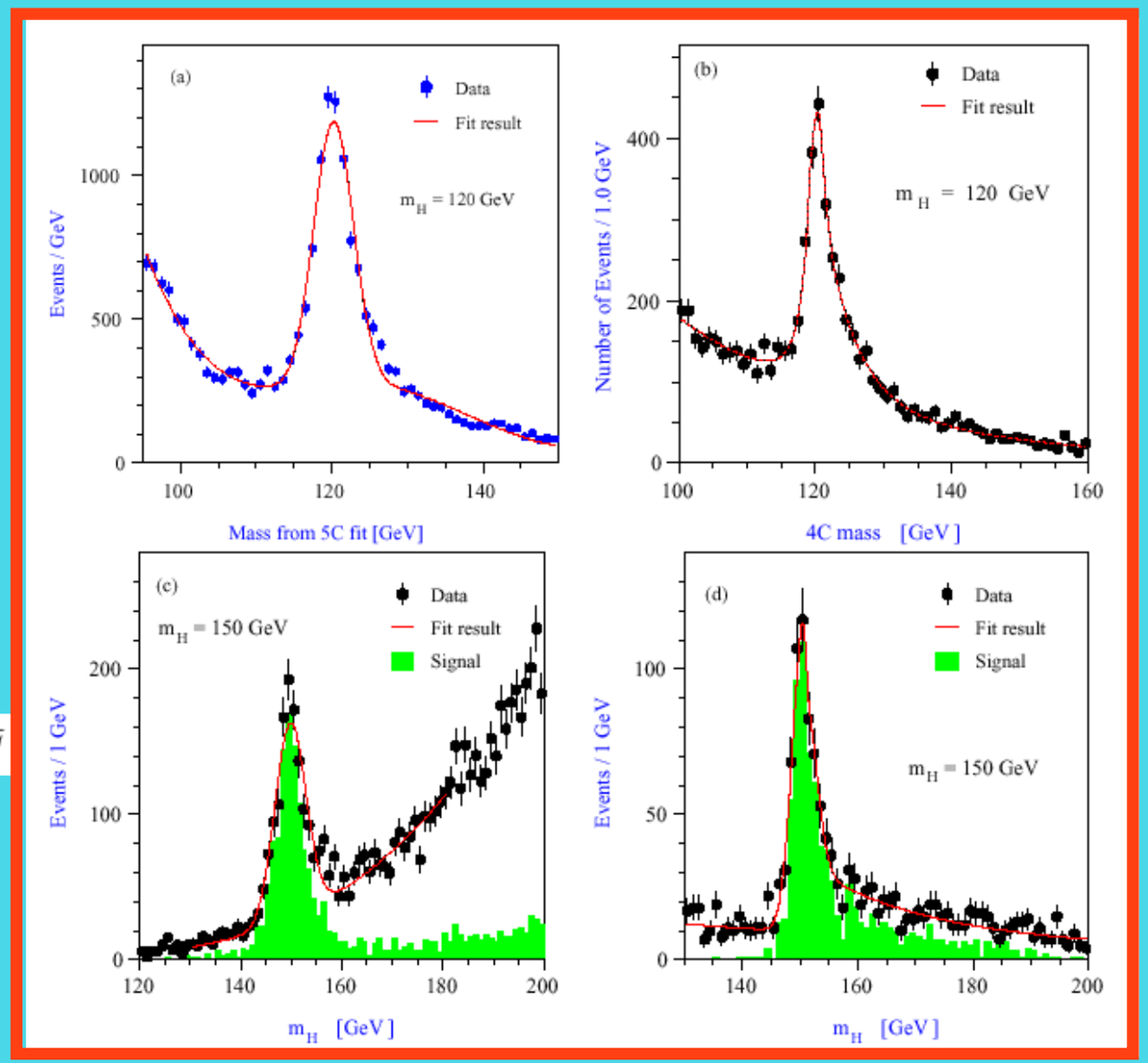

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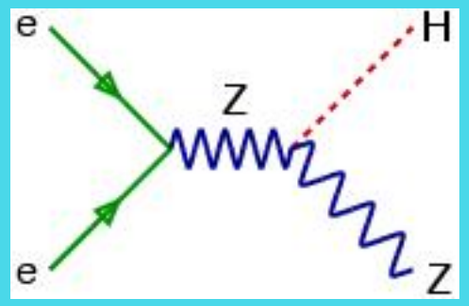

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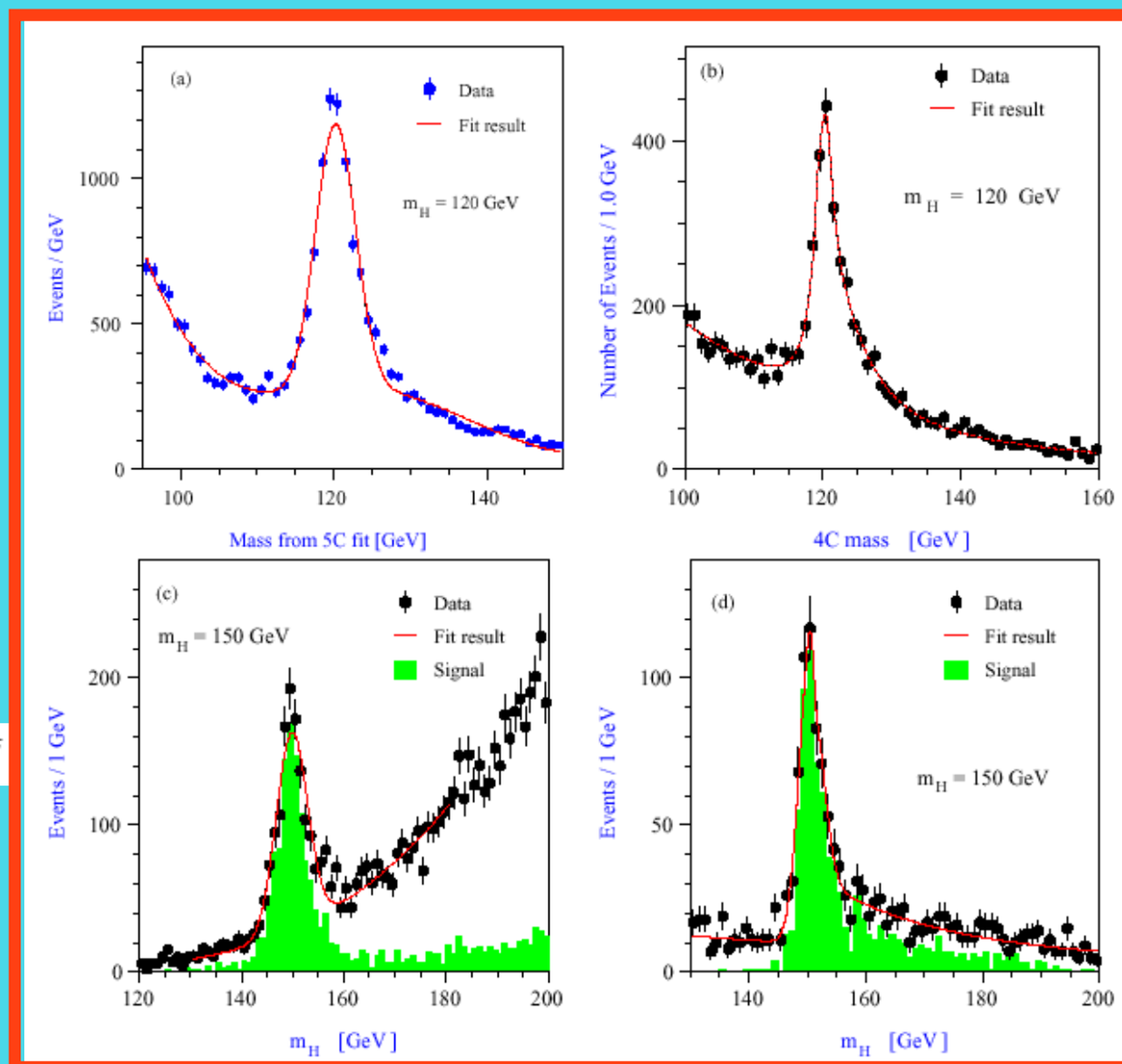

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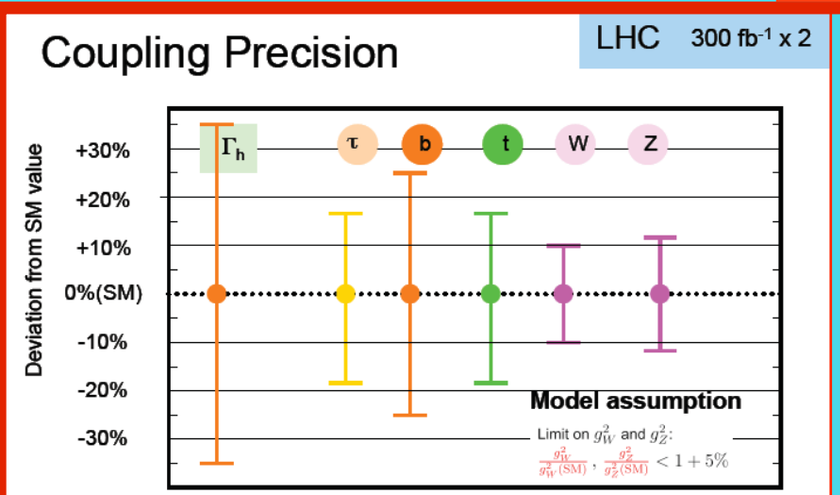

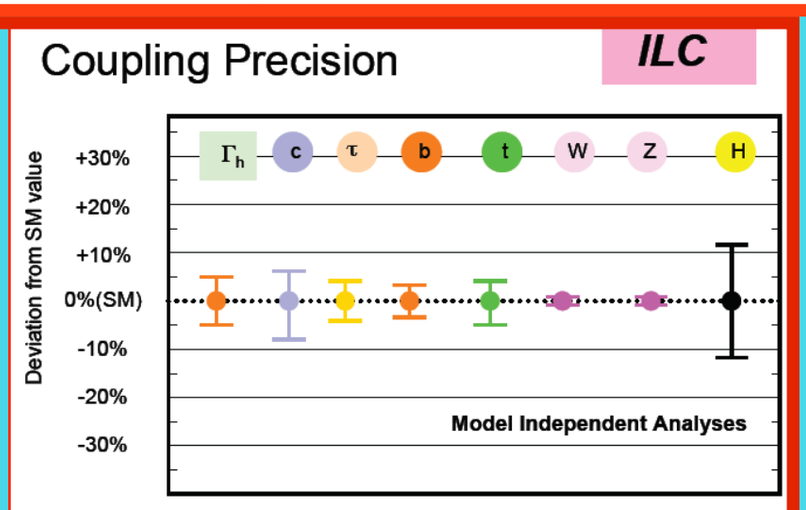

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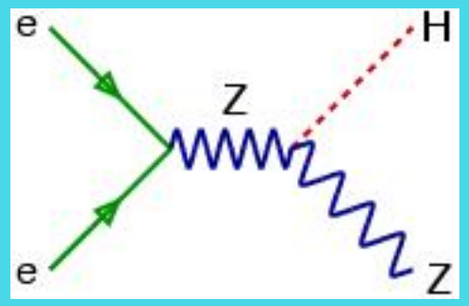

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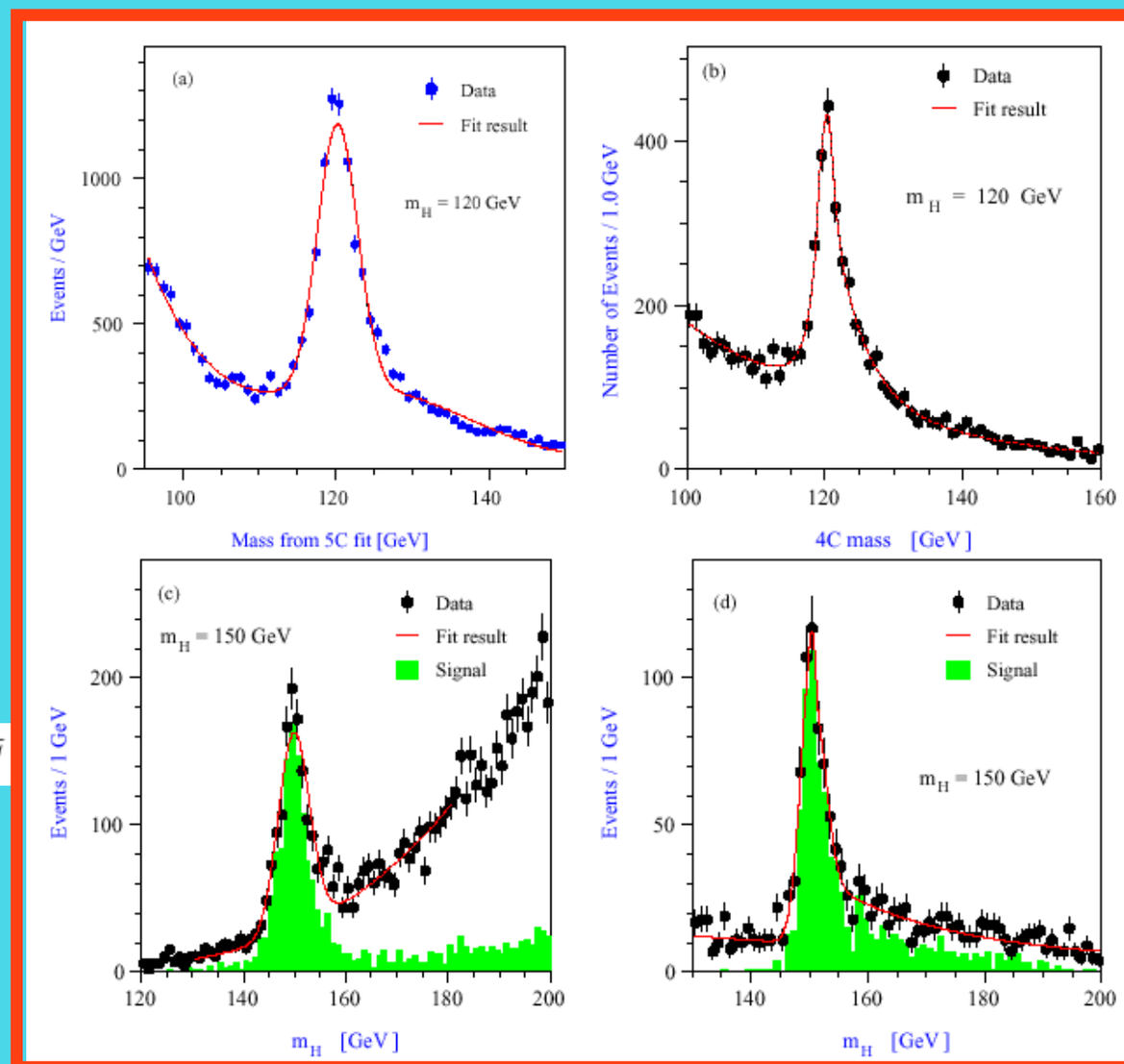

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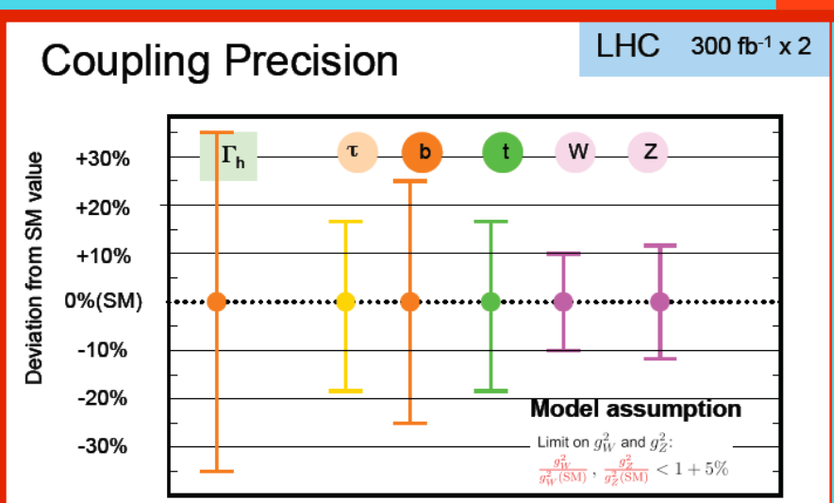

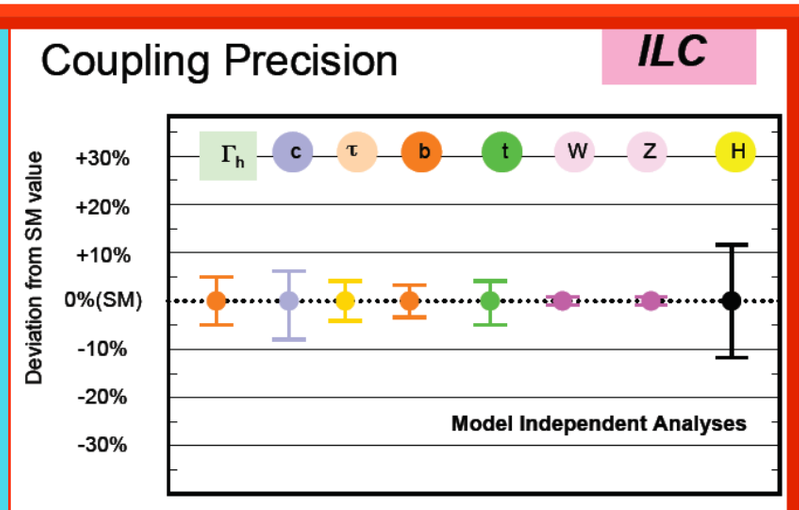

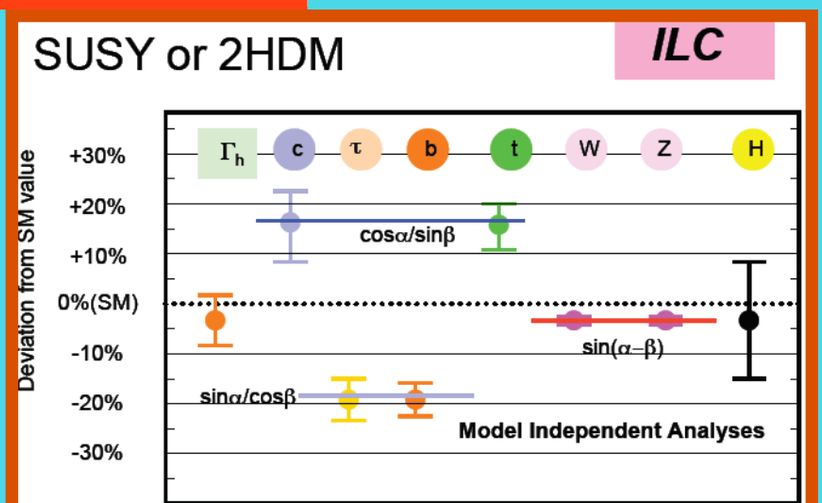

Neutrino Sector

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Neutrino masses

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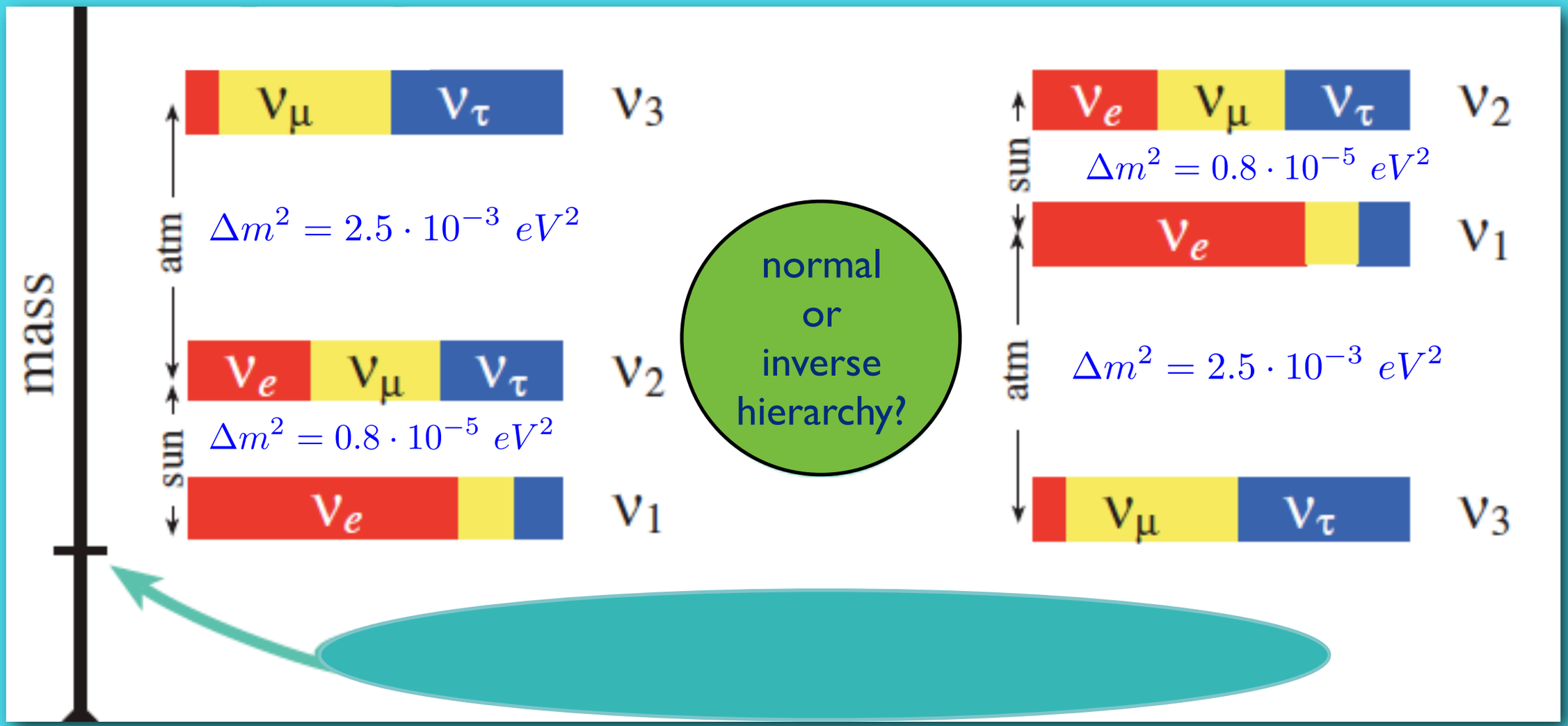

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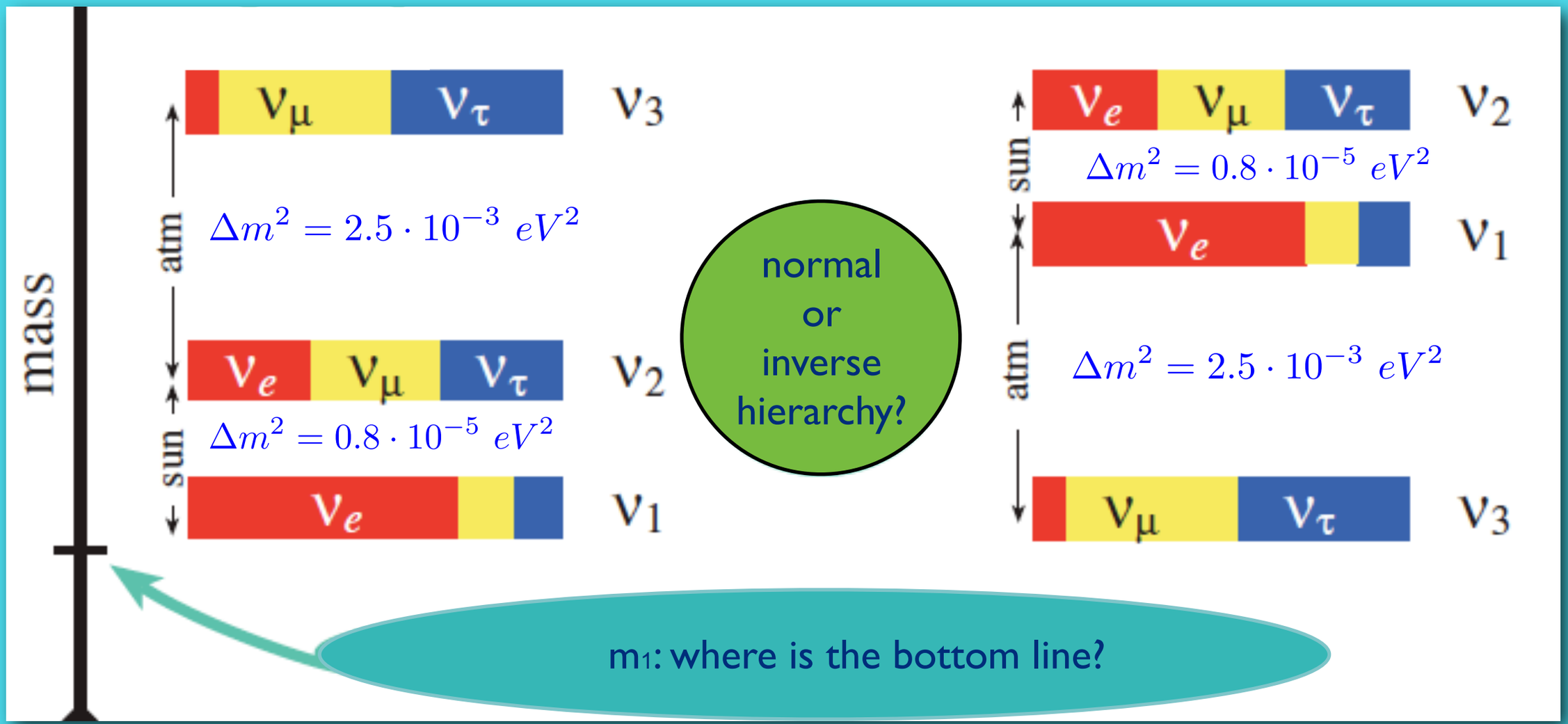

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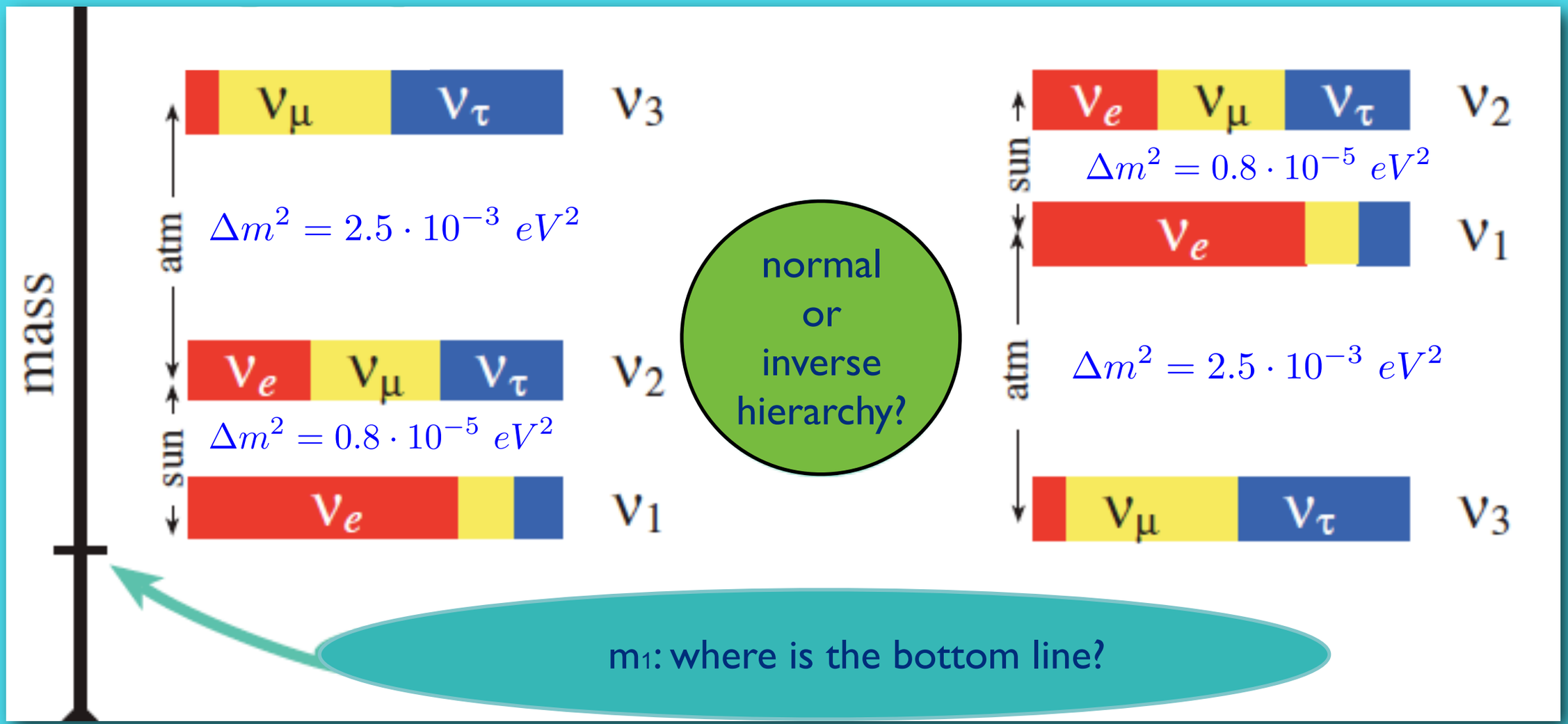

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cosmology: the CMB spectrum

Planck

Neutrino Sector

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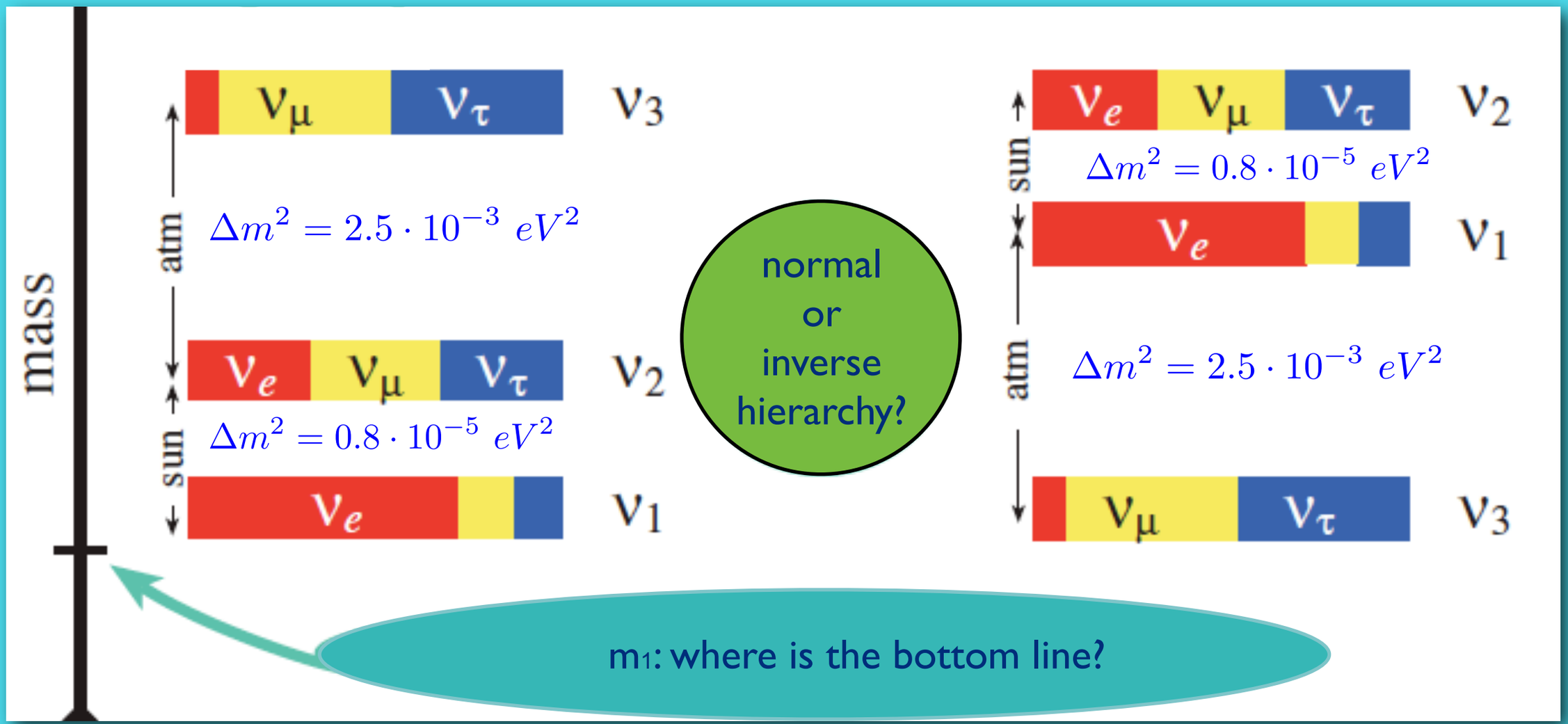

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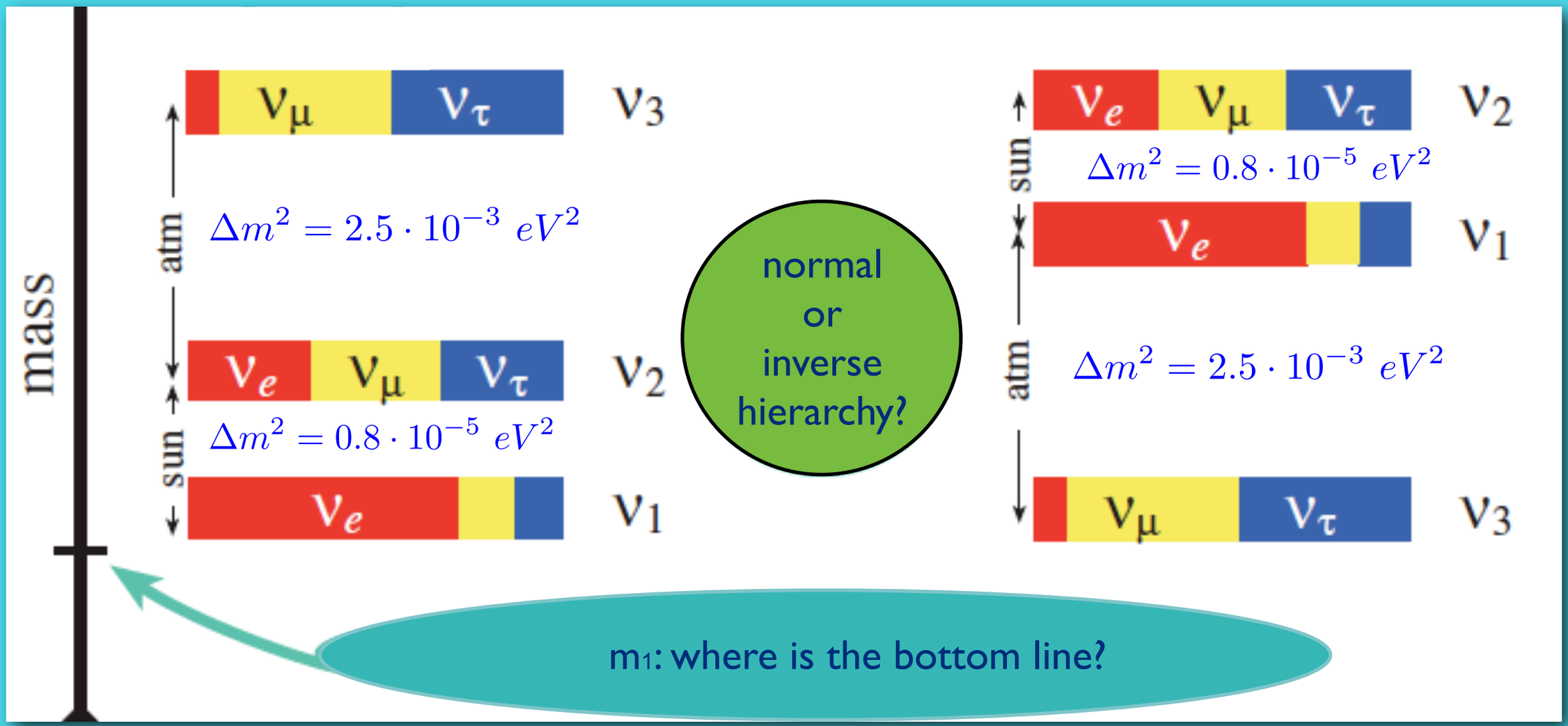

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KATRIN

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Dirac or Majorana?

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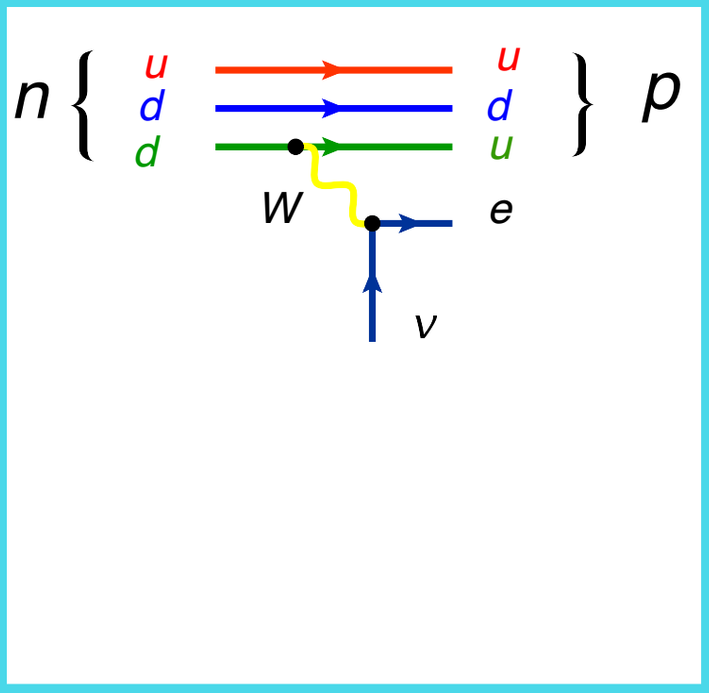

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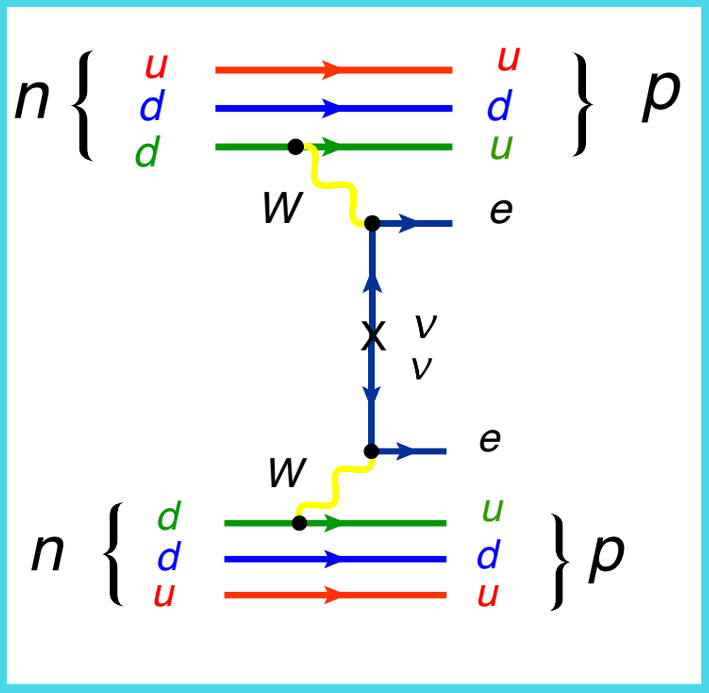

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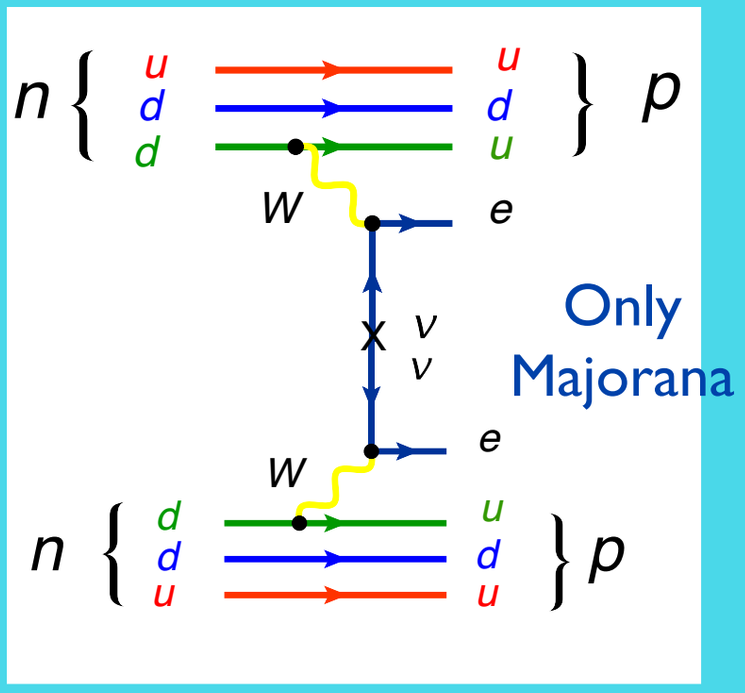

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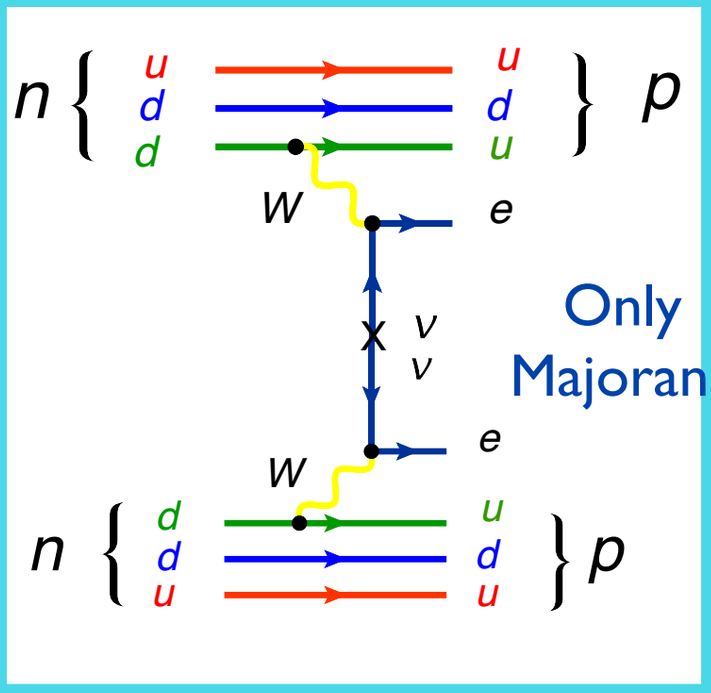
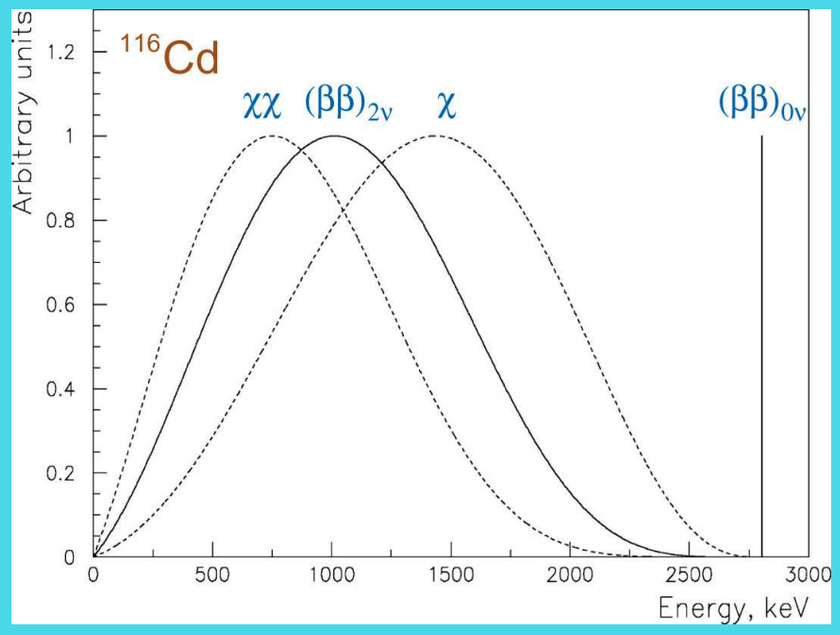
$$m_{\nu_{M_1}} \neq m_{\nu_{M_2}}$$

0νββ decay



Only Majorana



Neutrino Sector

Dirac or Majorana?

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

$$\nu_D \neq \nu_D^*$$
$$m_{\nu_L} = m_{\nu_R}$$

?

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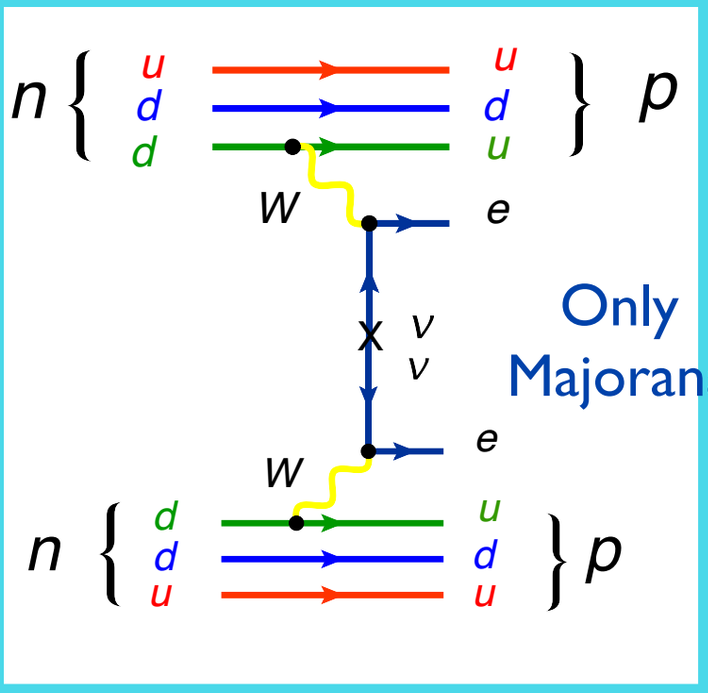
0νββ decay



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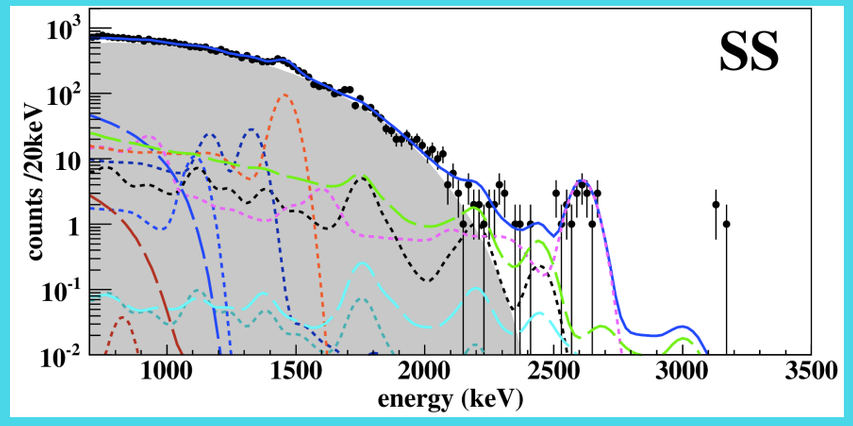

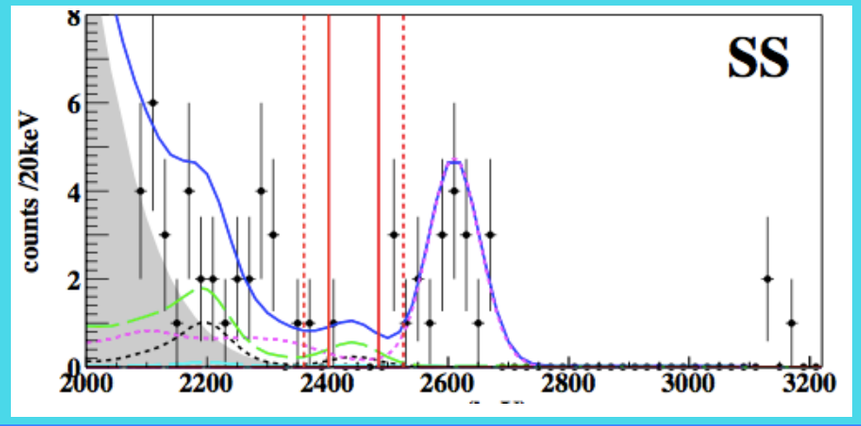

Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

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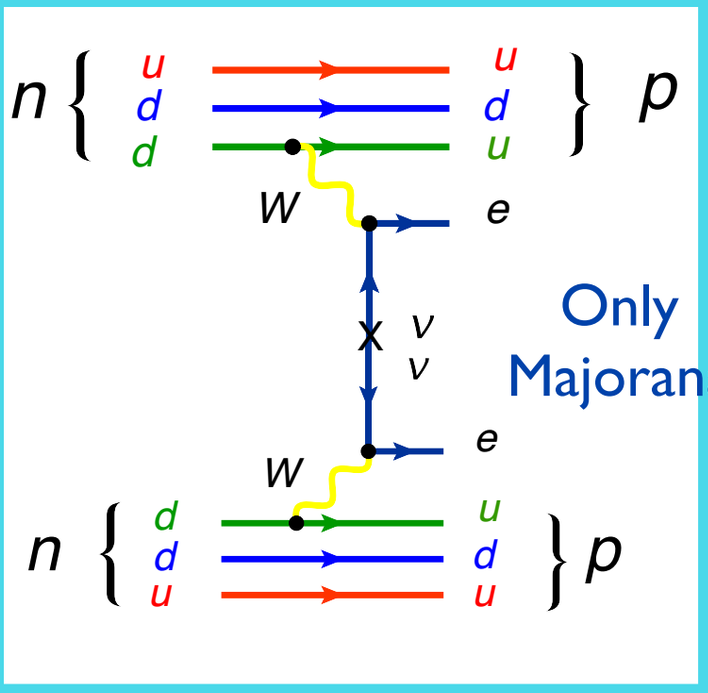

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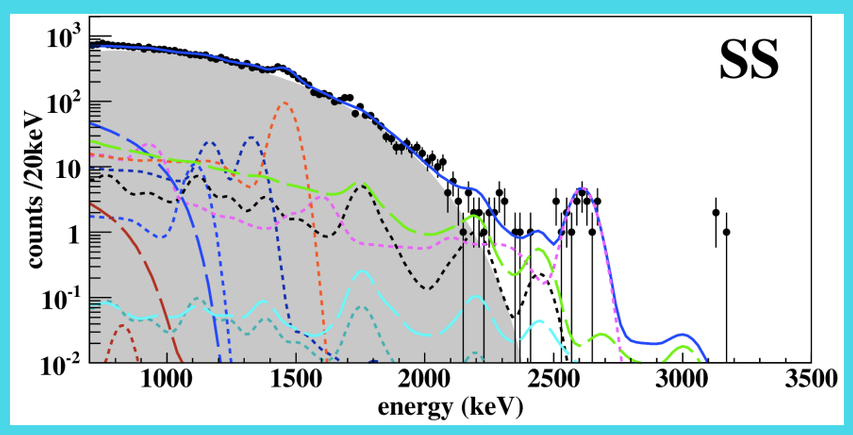

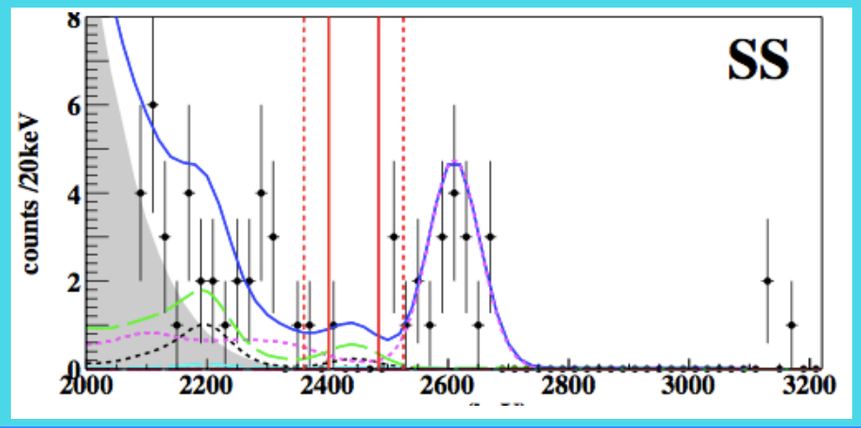

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$T_{1/2}2\nu\beta\beta$ (^{136}Xe) x 10^{21} yr = 2.23 ± 0.017 stat ± 0.22 sys

Neutrino Sector

Dirac or Majorana?

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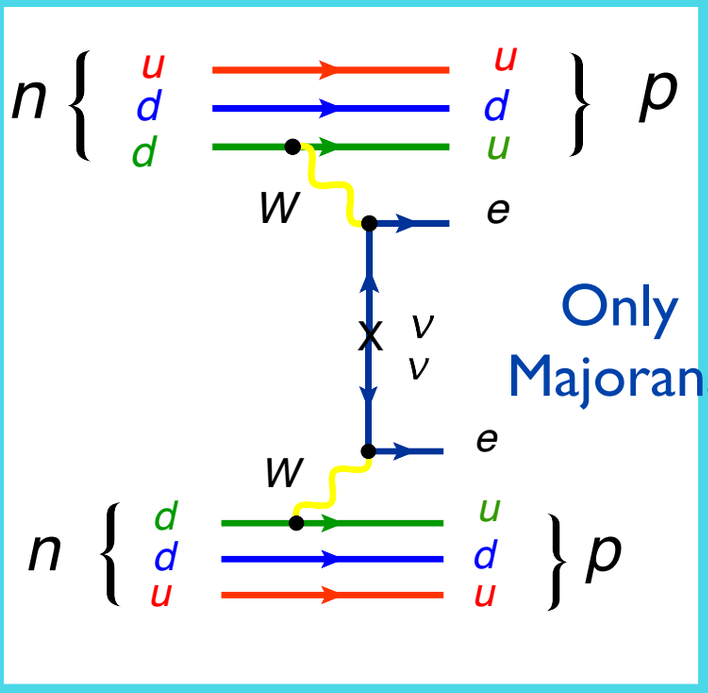

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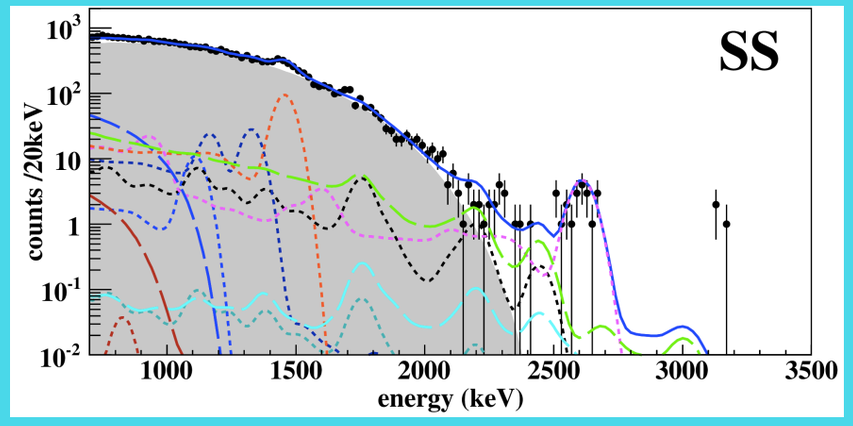

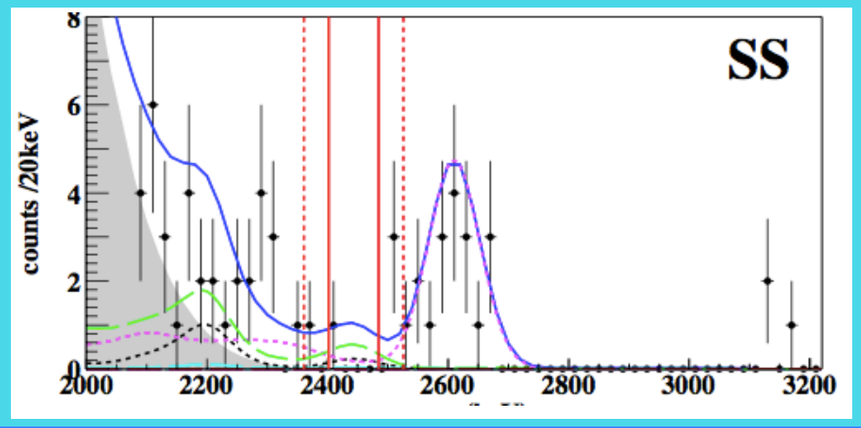

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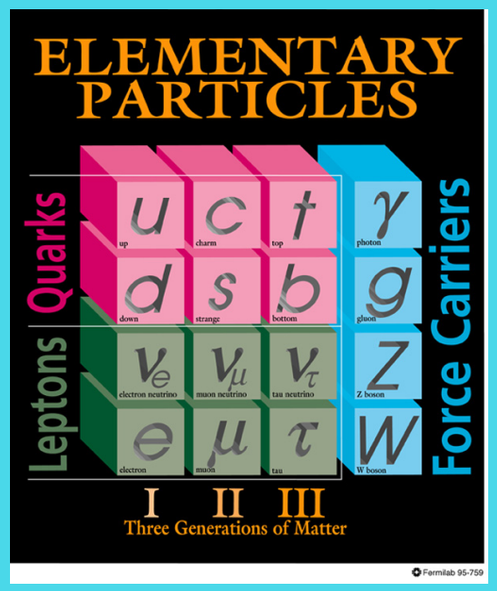
$T_{1/2}0\nu\beta\beta$ (^{136}Xe) x 10^{25} yr > 1.6 (90% CL)

Flavour Sector

Flavour Sector

- Number of Generations?



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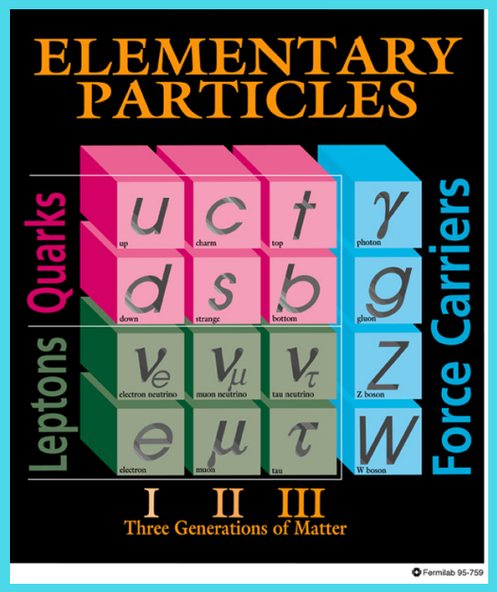
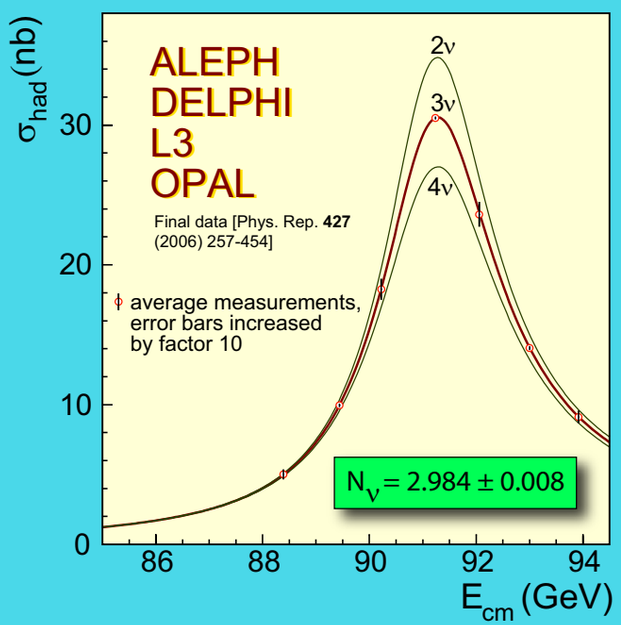


- The width of the Z-boson (LEP)



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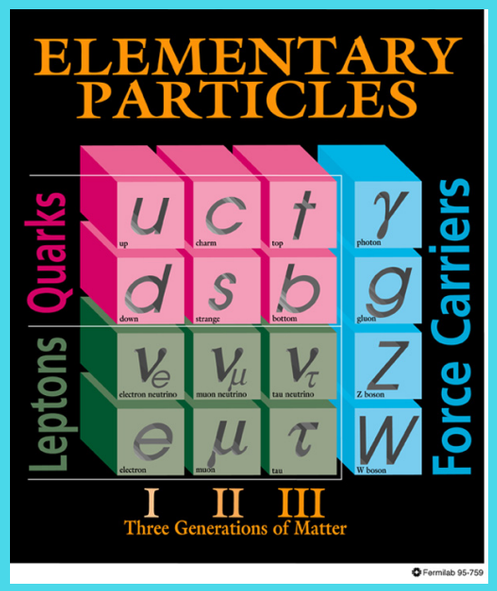

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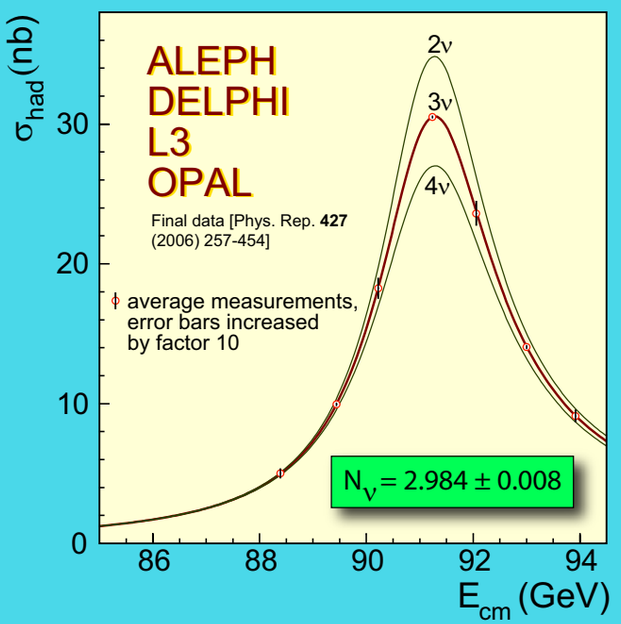

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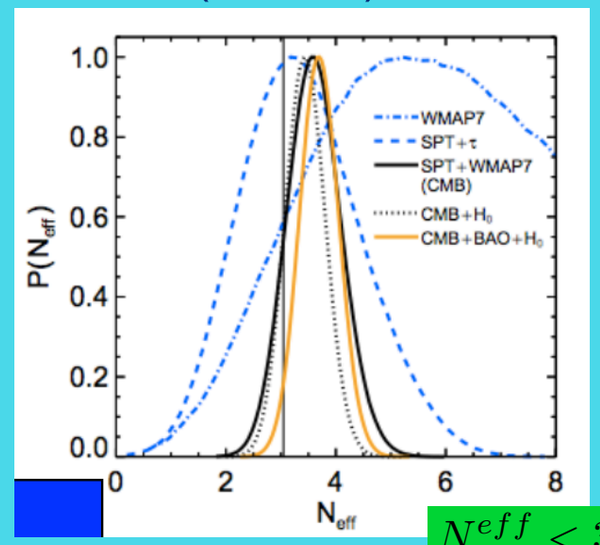

$N_\nu^{eff} < 3.30 \pm 0.27$

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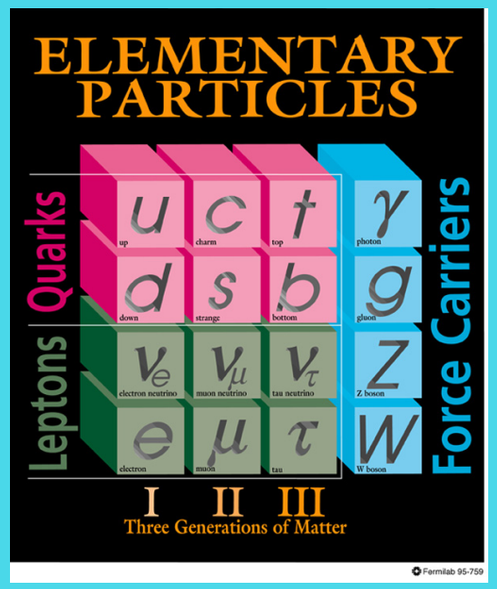

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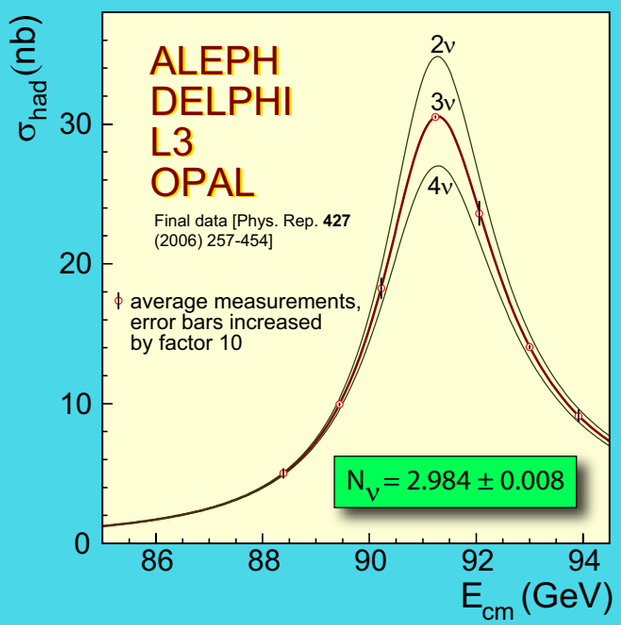

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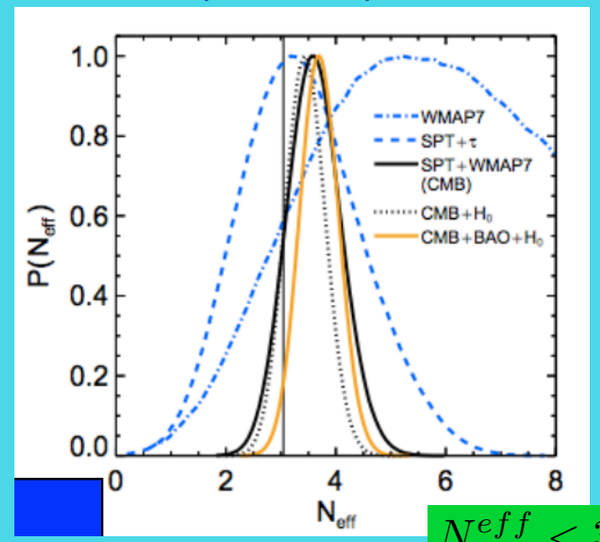

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- Why 3 copies?

Flavour Sector

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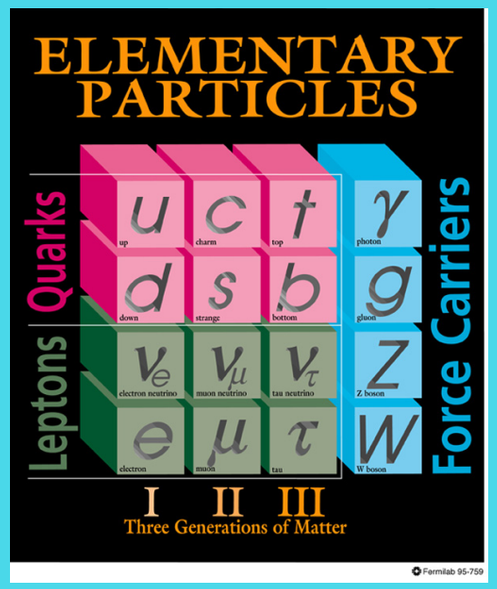

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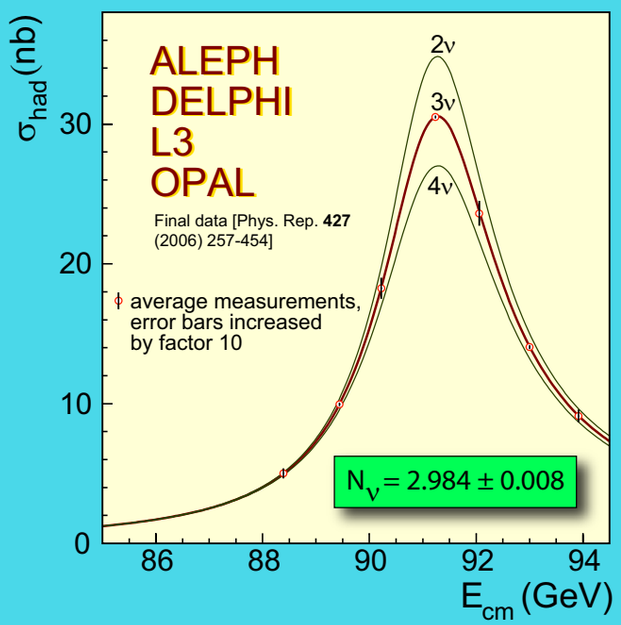

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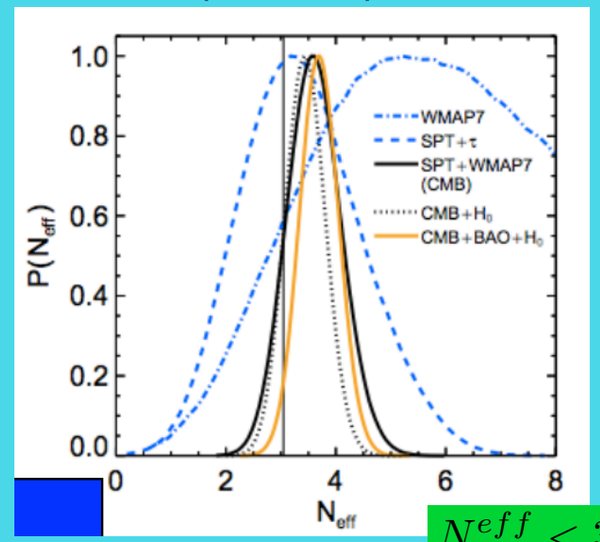

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Flavour Sector

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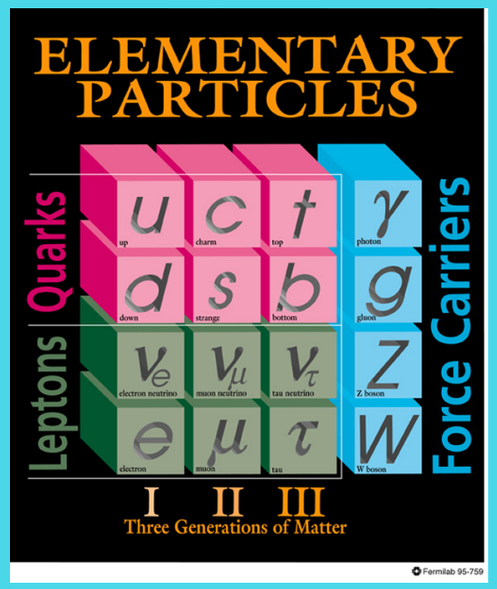

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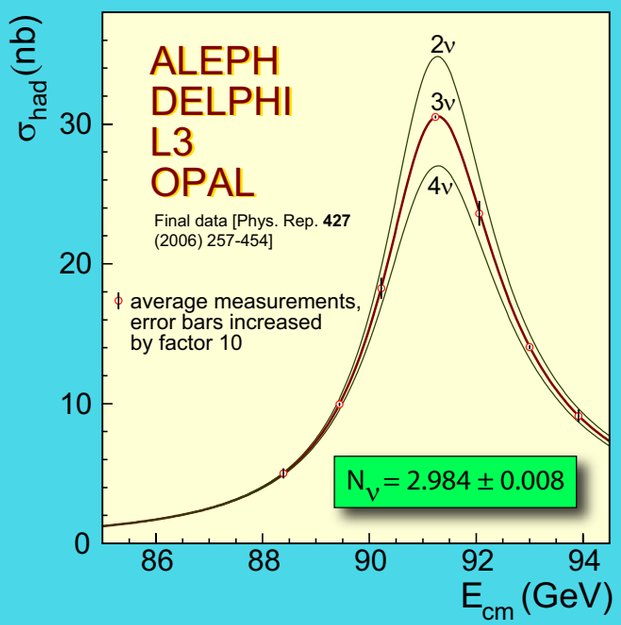

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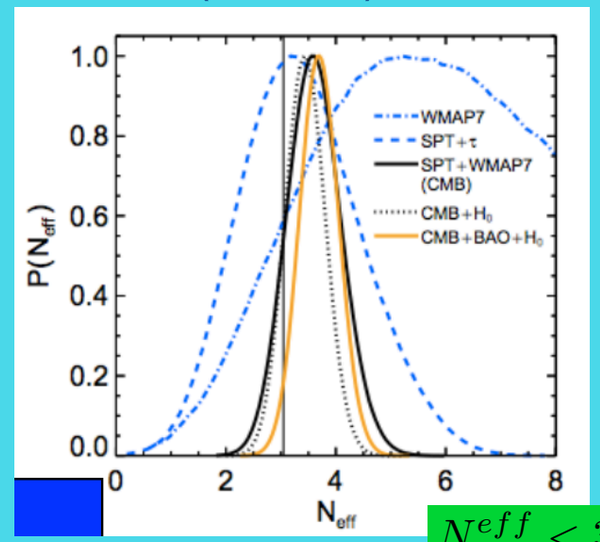

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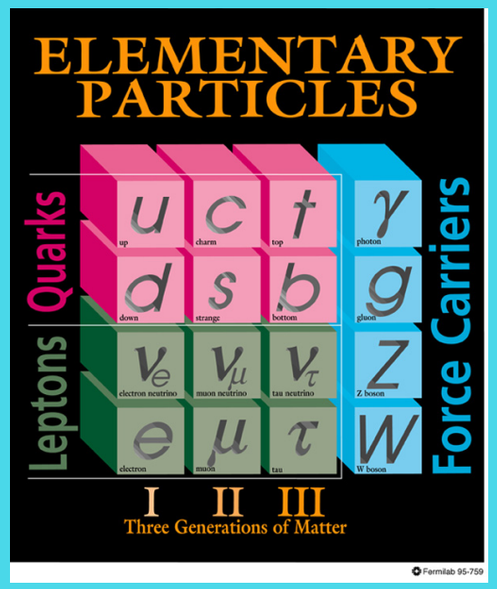

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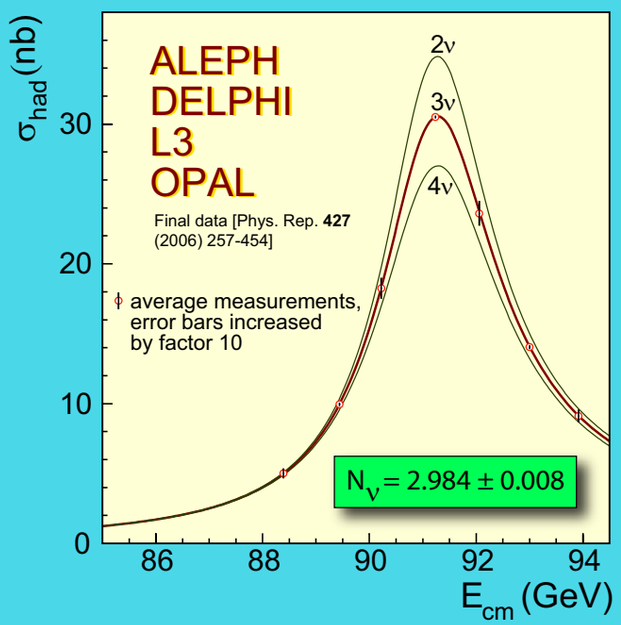

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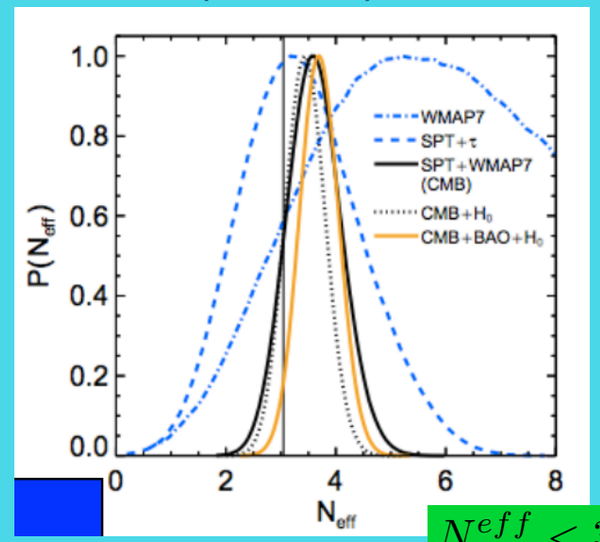

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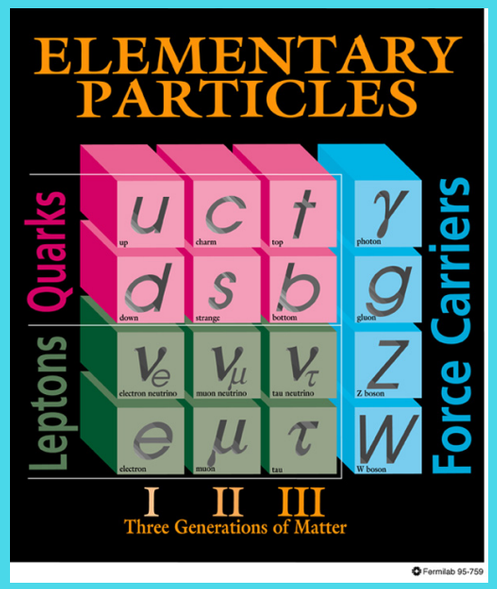

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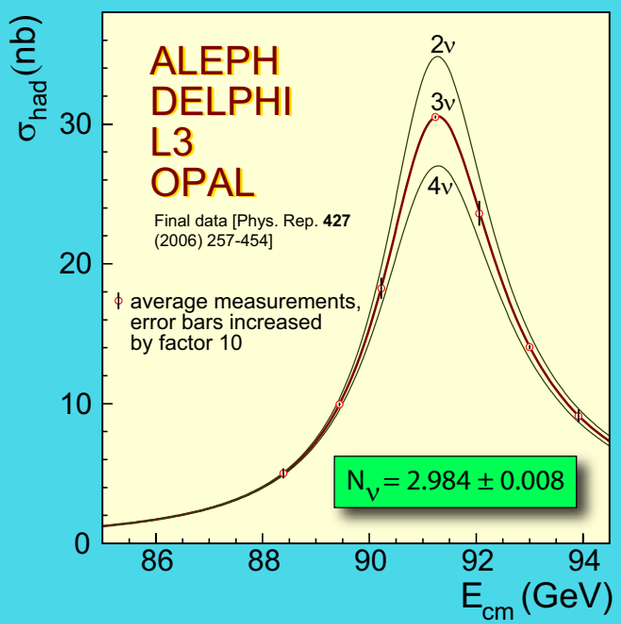

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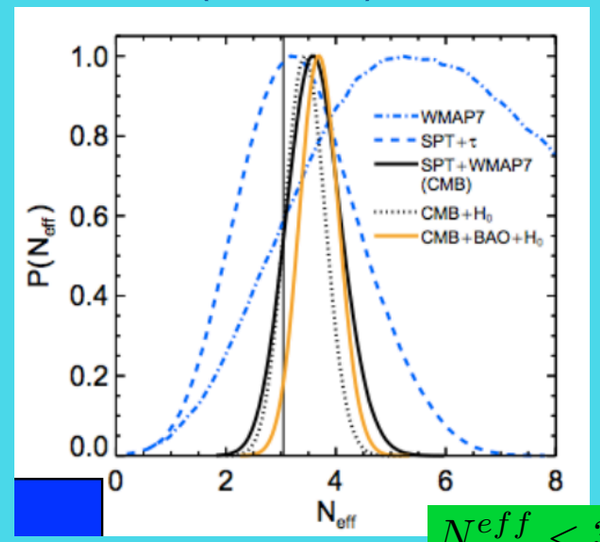

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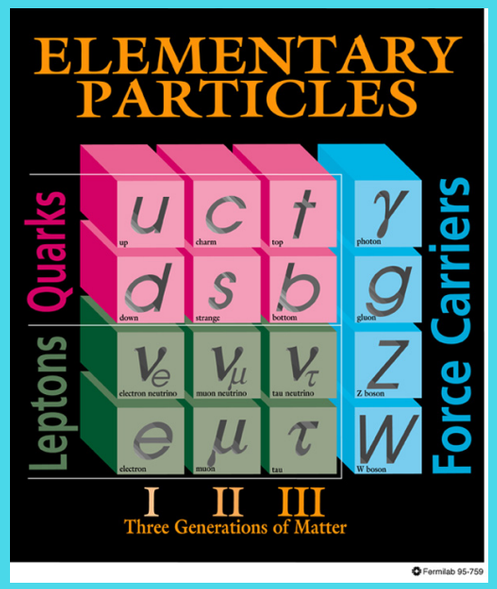

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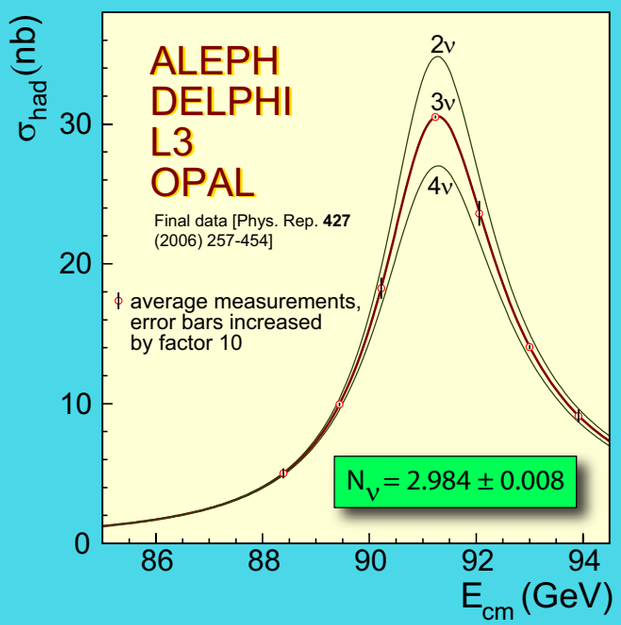

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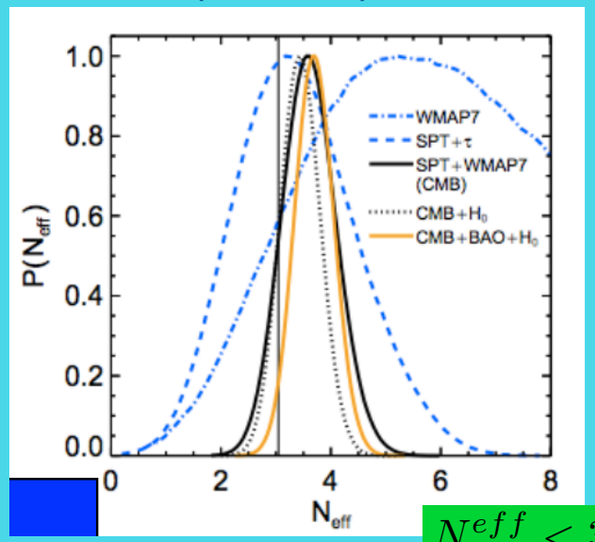

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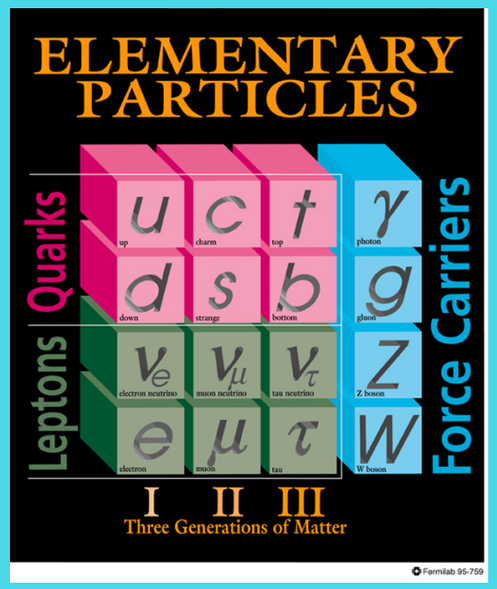

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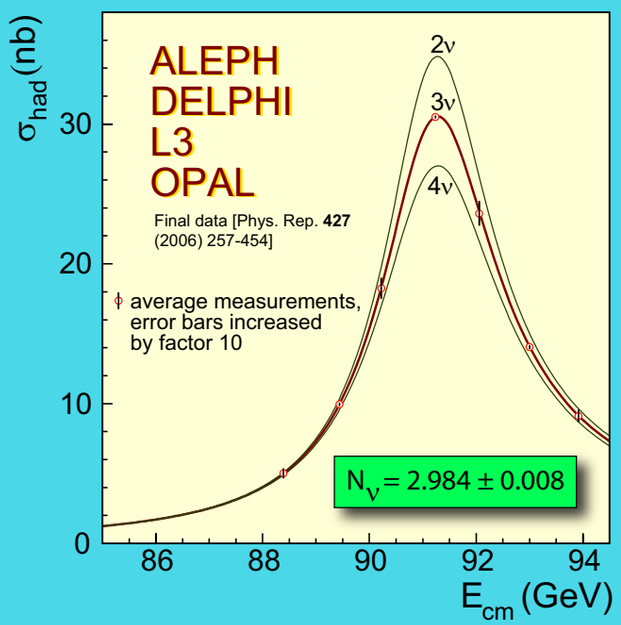

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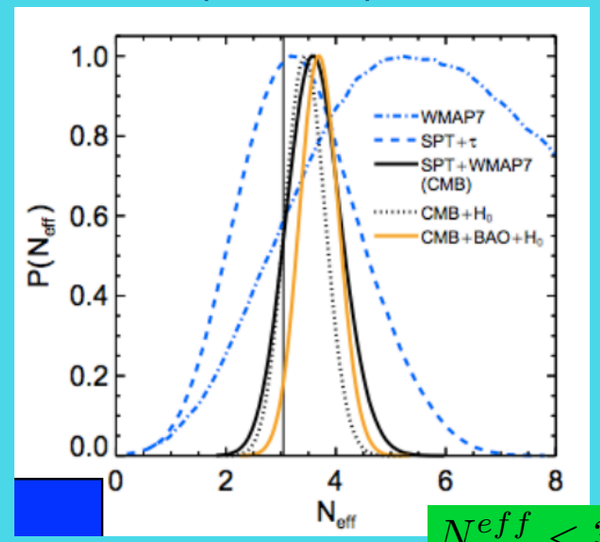

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- The fourth generation is excluded also by precision measurement of rare decays

The Mass Spectrum and Mixing

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- Mass spectrum?

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$$m_{lepton} = y_{lepton} \cdot v$$
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SM

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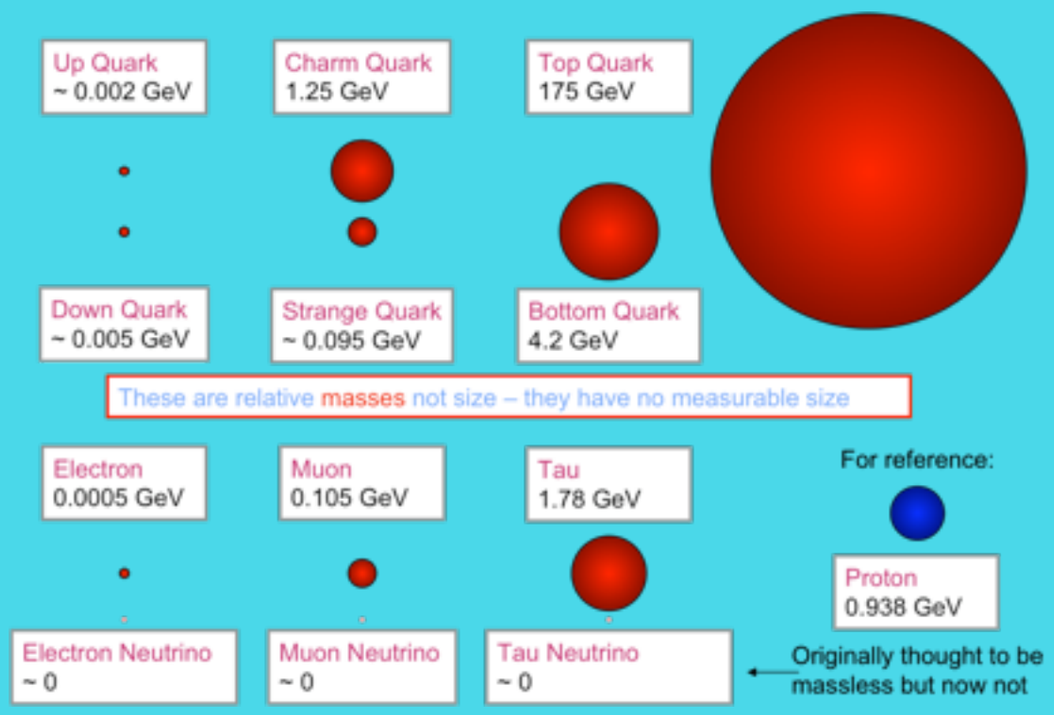

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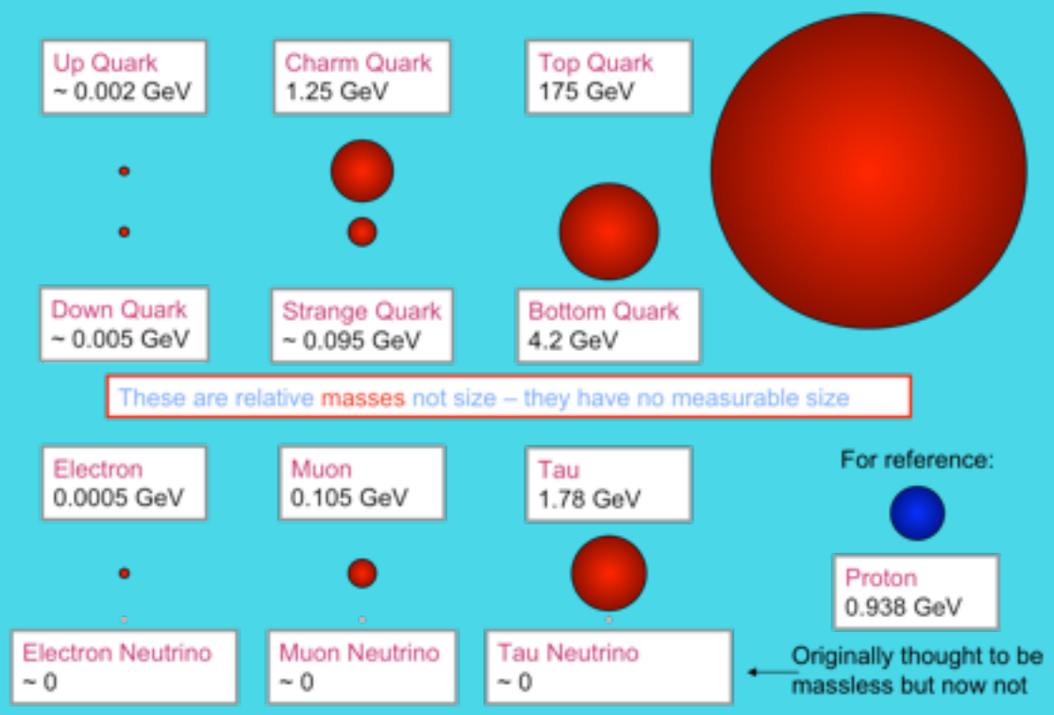

- Mixing Matrices?

The Mass Spectrum and Mixing

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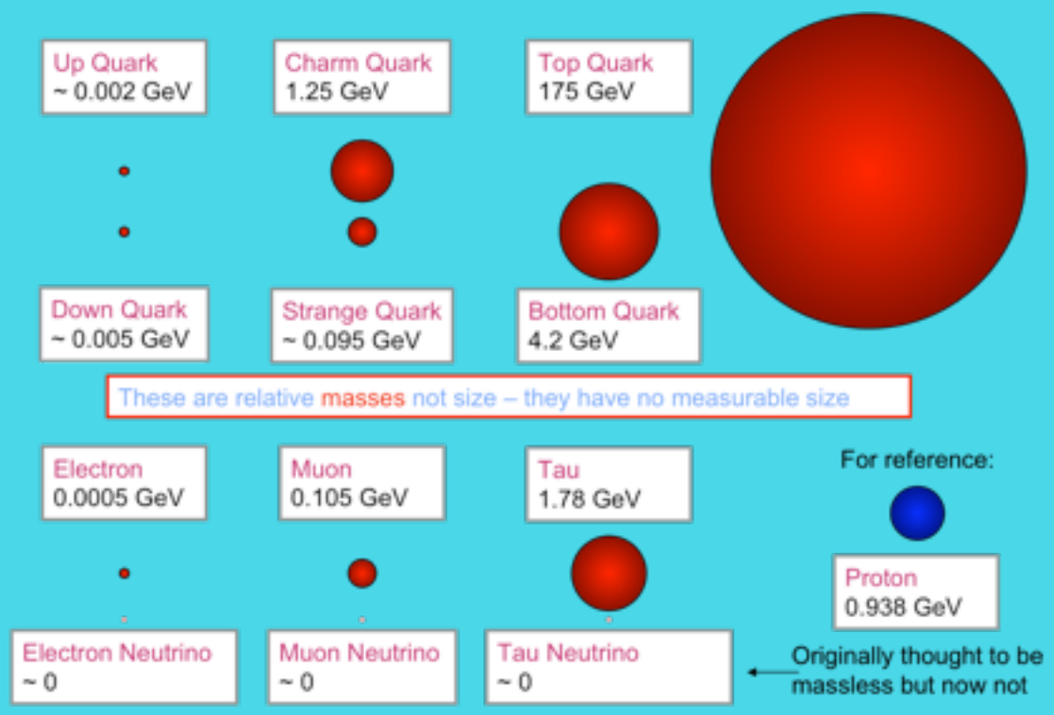
SM

- Mixing Matrices?
- Quark-Lepton Symmetry



The Mass Spectrum and Mixing

- Mass spectrum?

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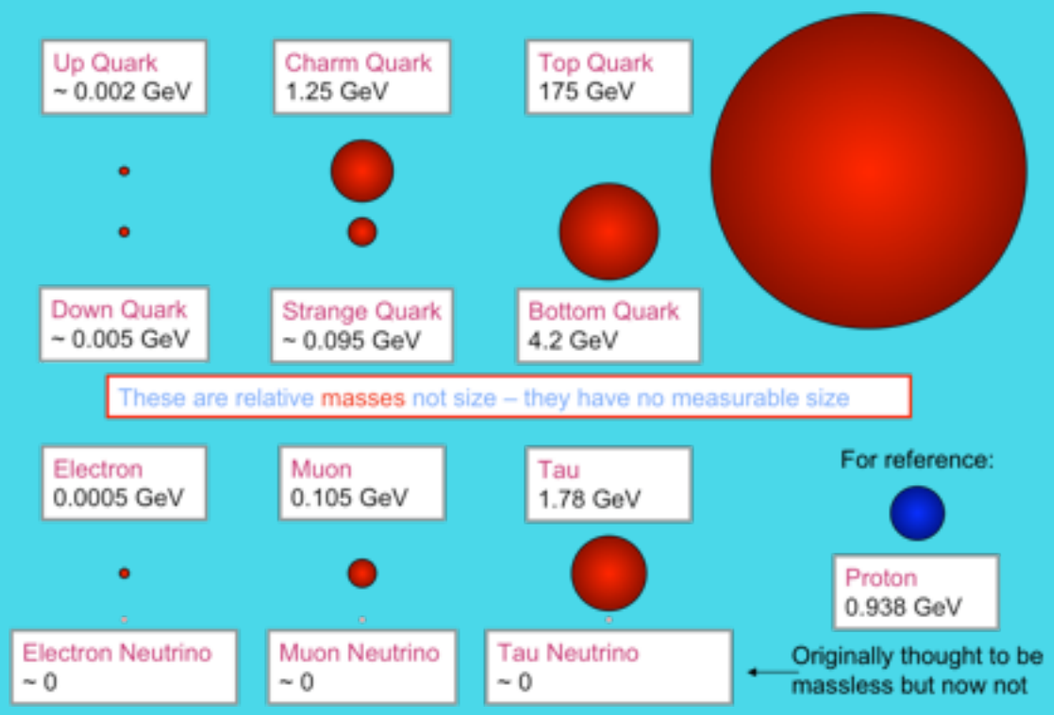

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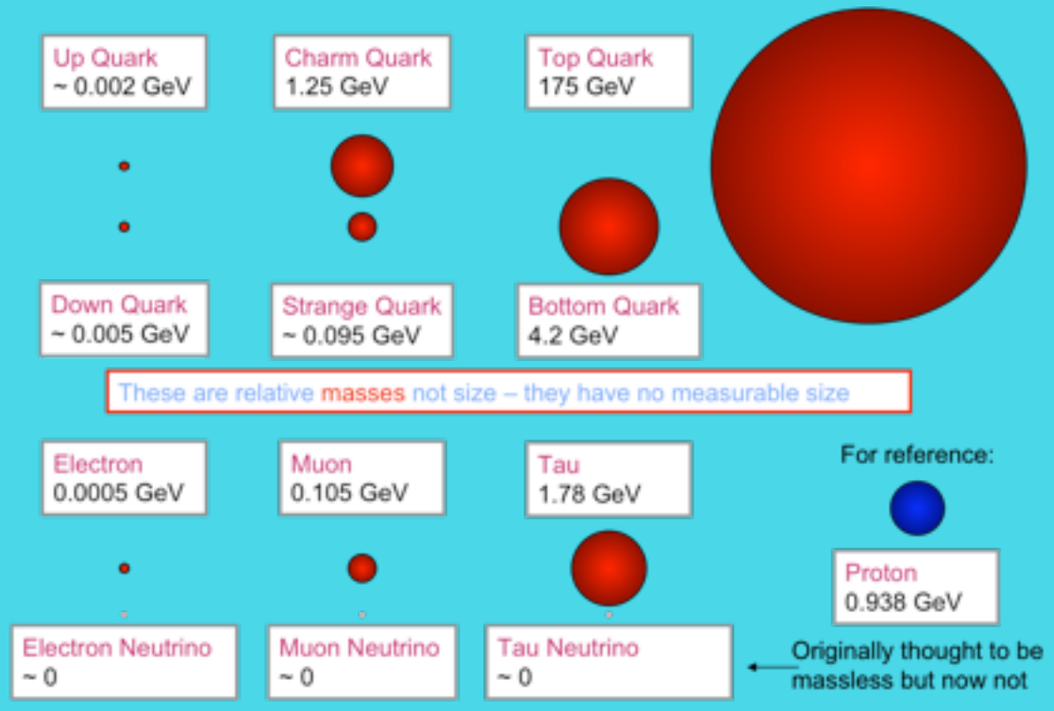

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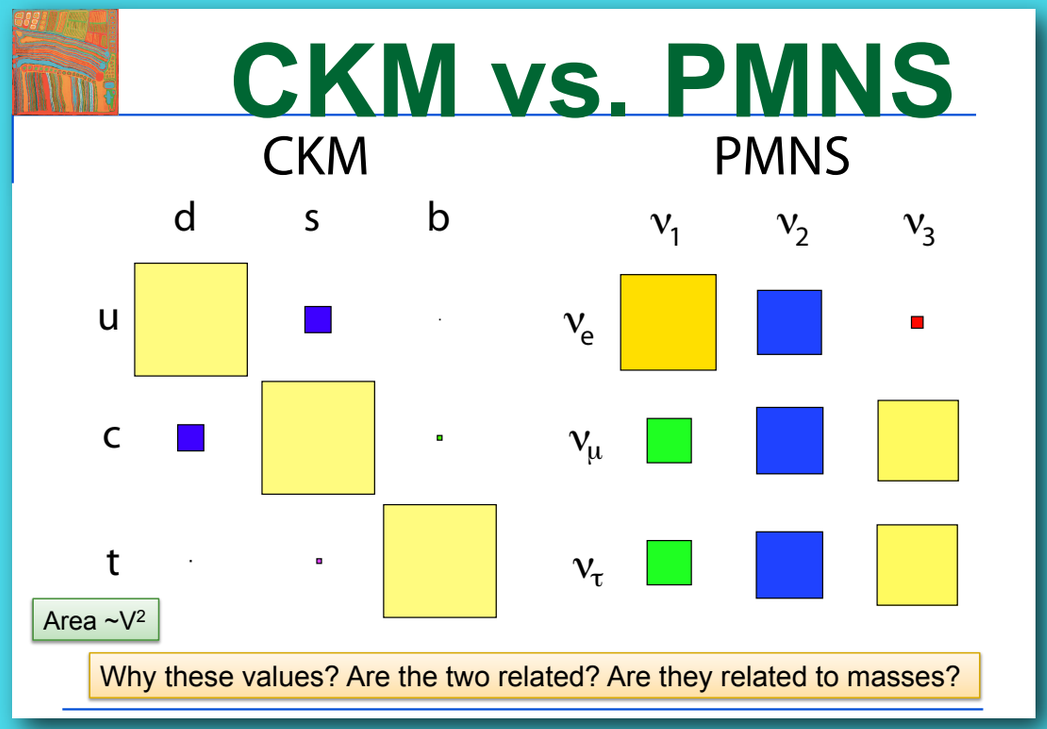

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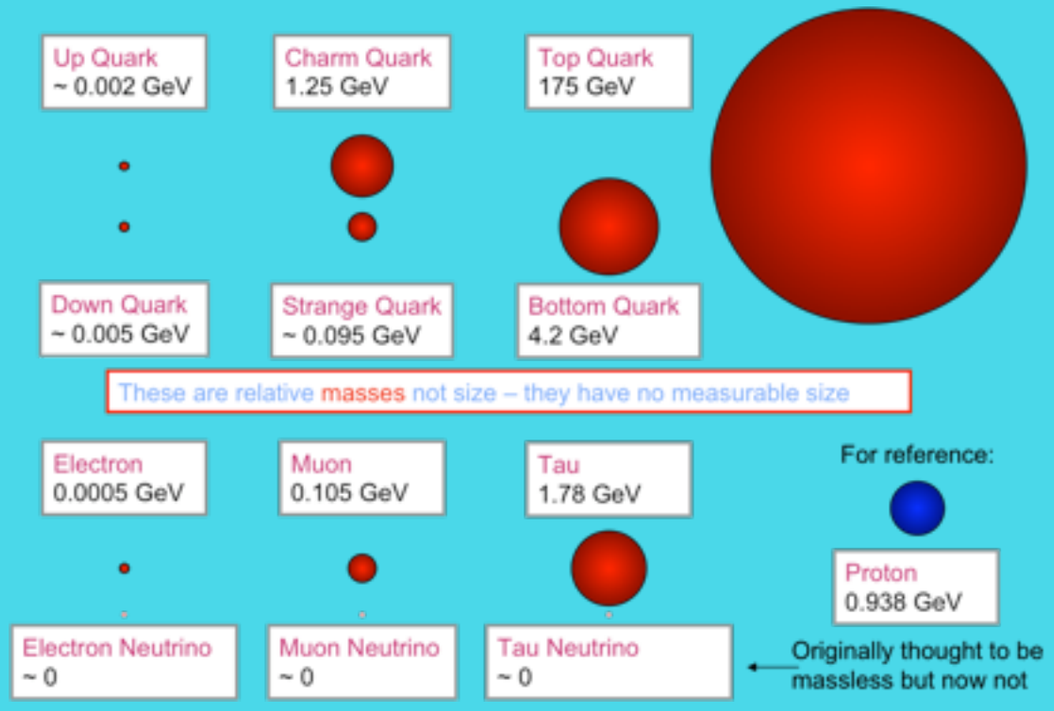

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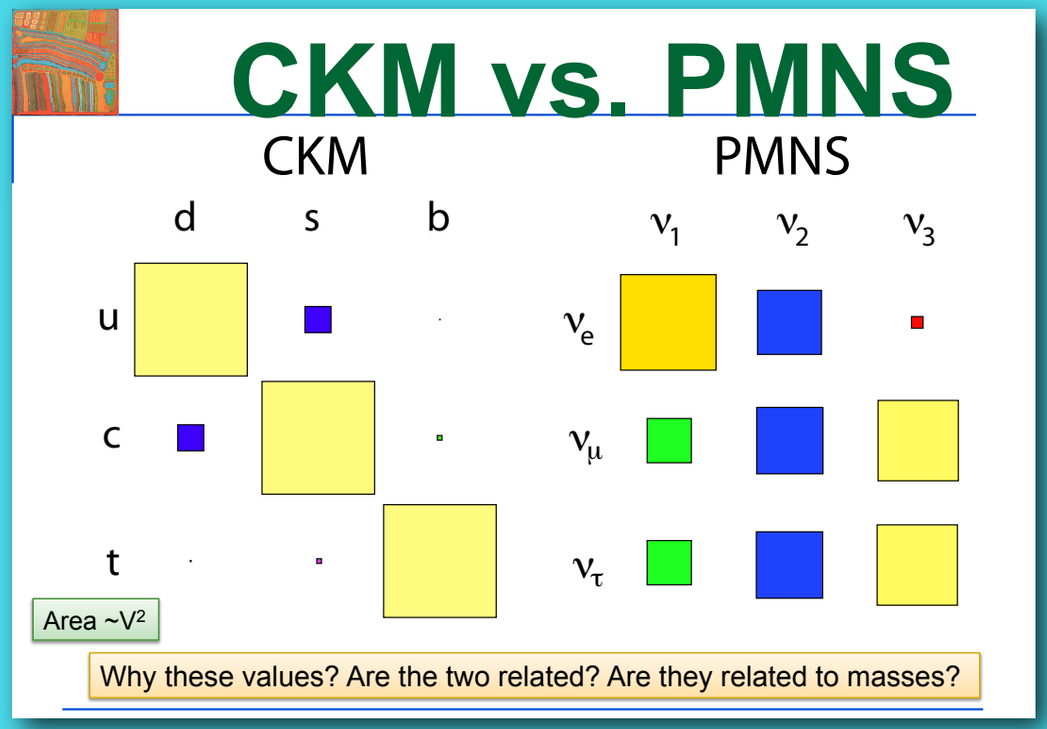

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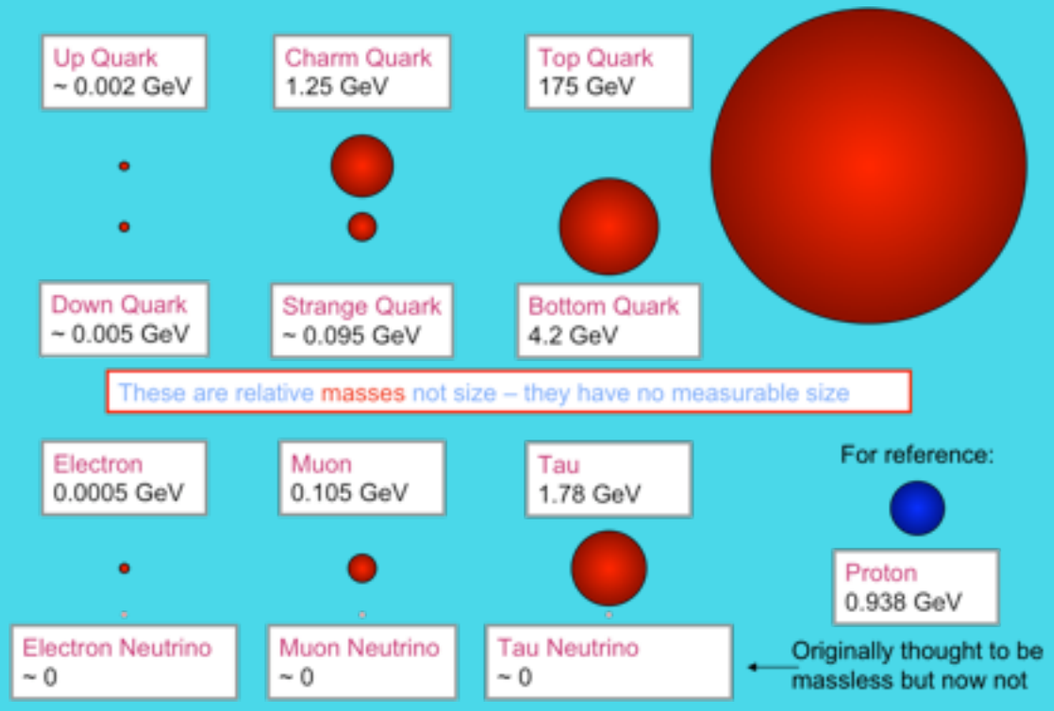

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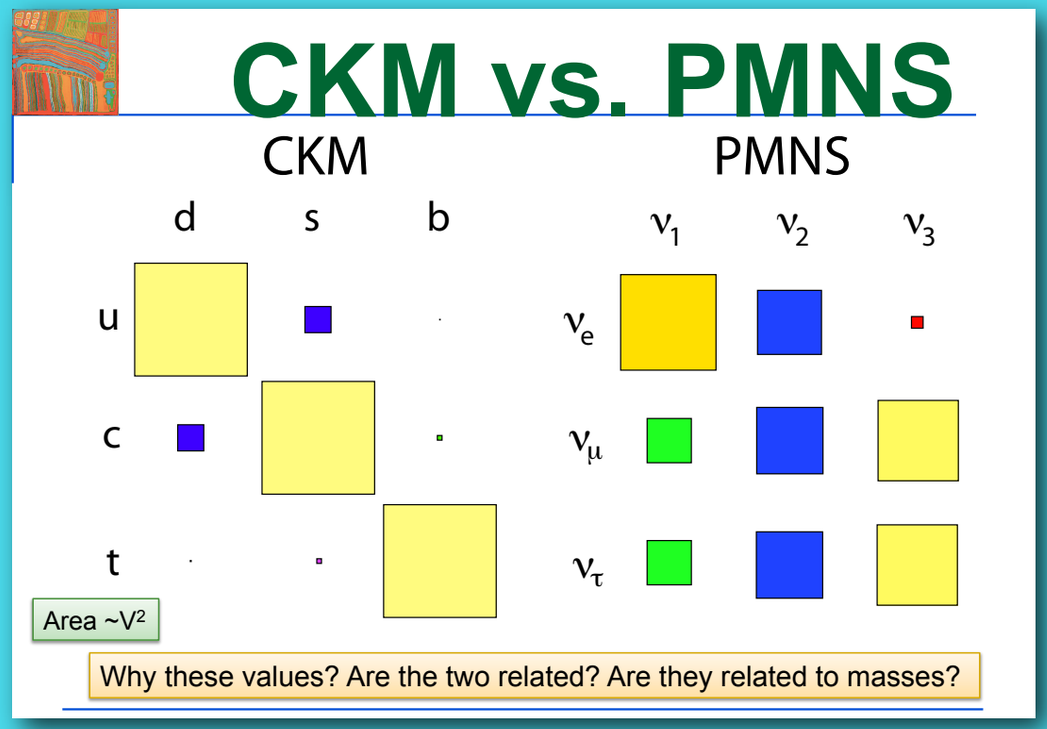
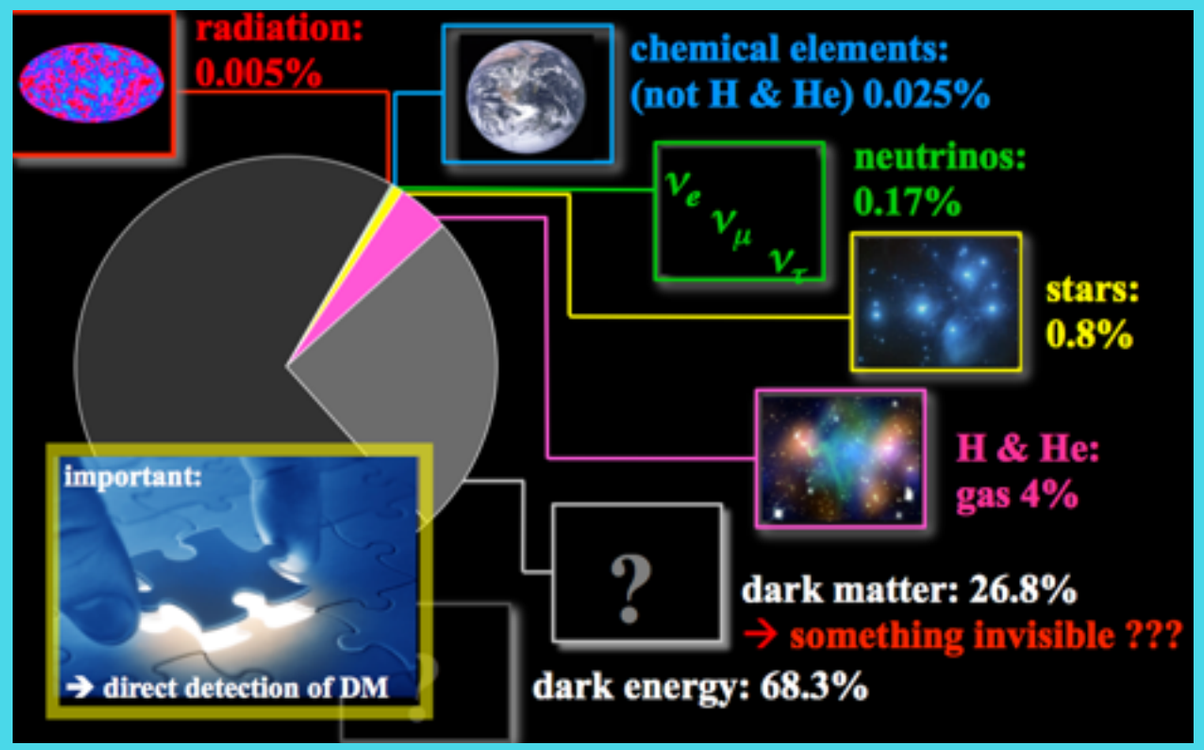
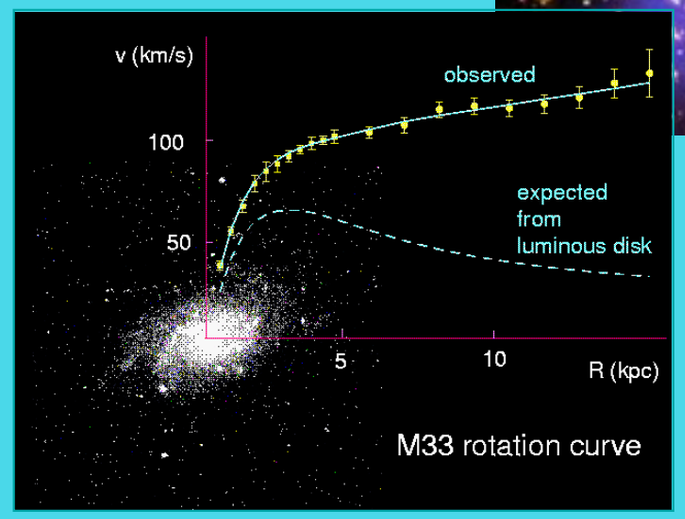
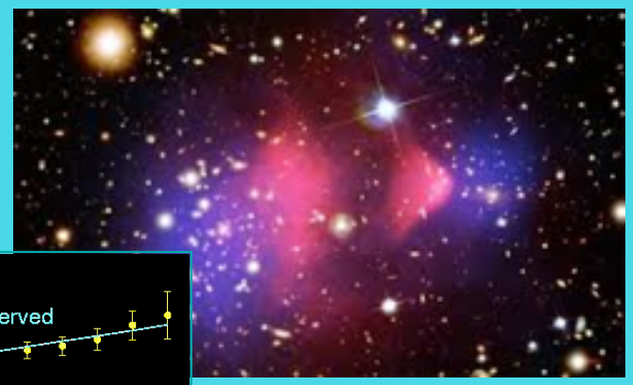


- What re the CKM and PMNS phases?
- Where lies the source of CP violation: in qurk or lepton sector?

Dark Matter







- rotation curves of stars
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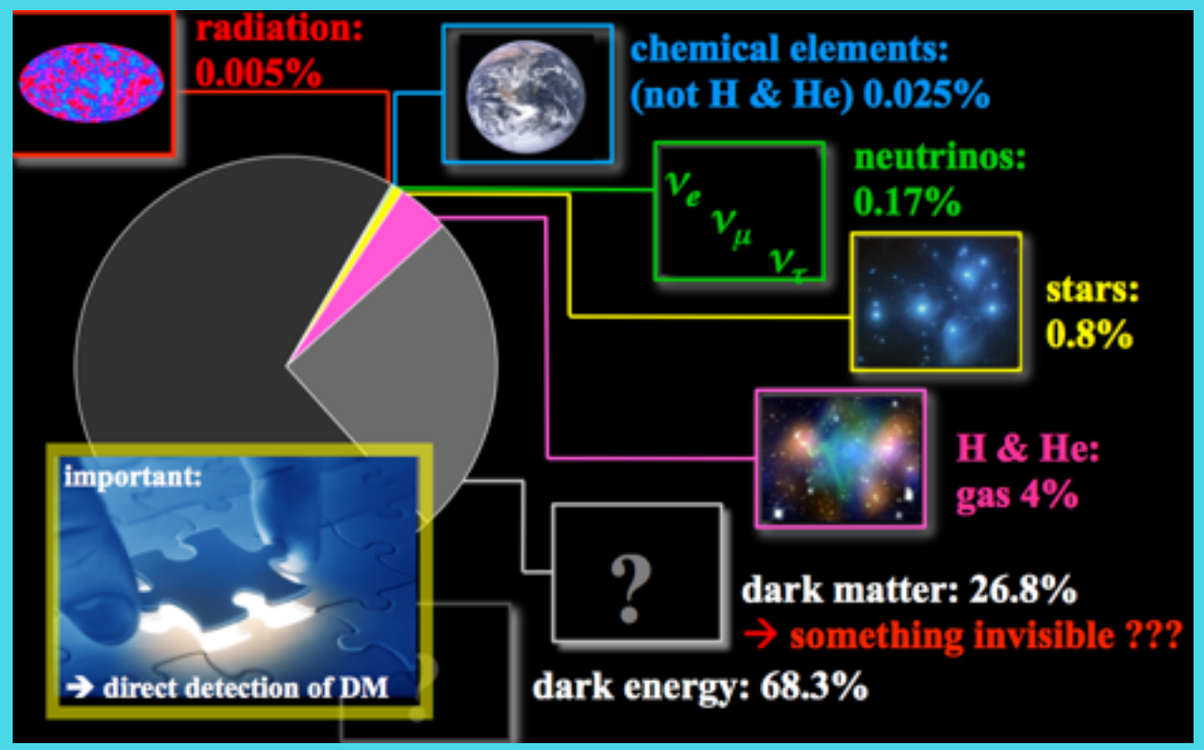

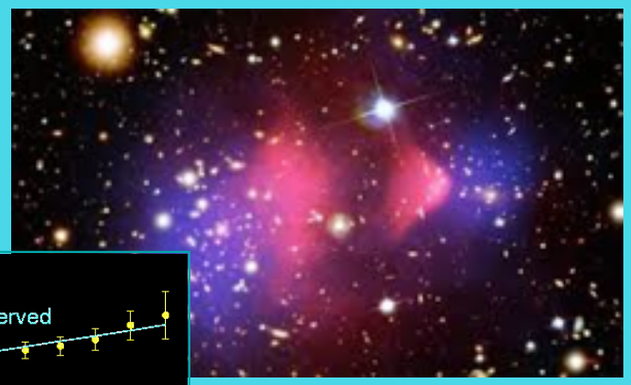

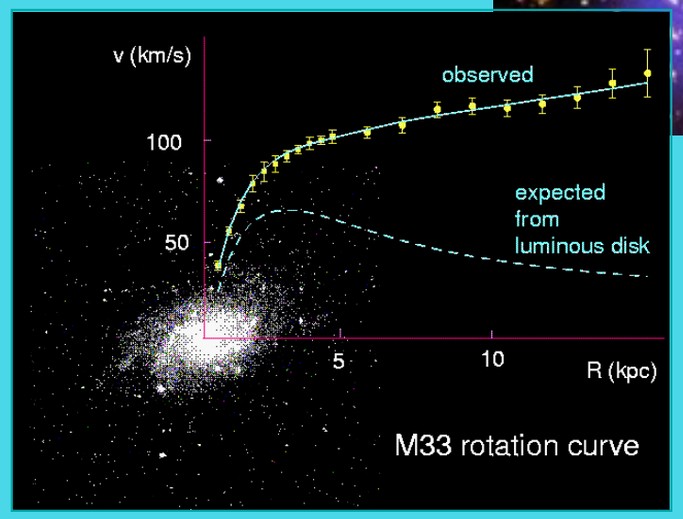

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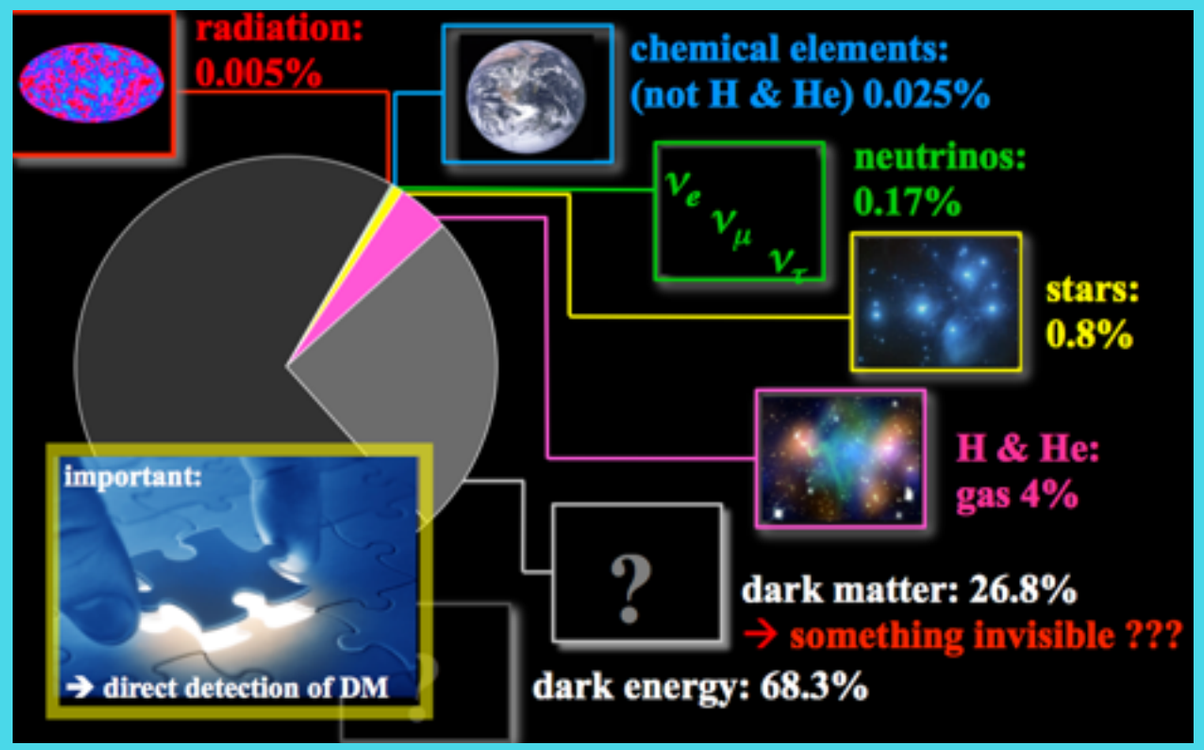

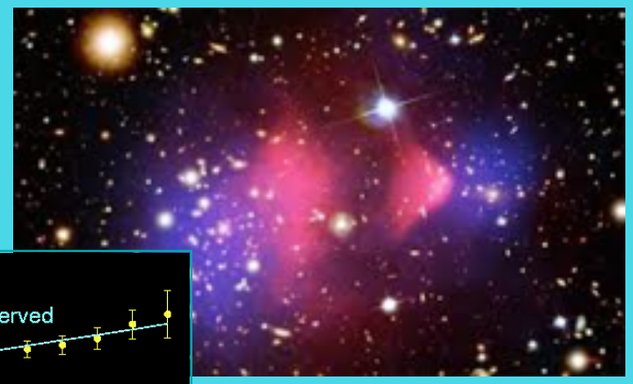

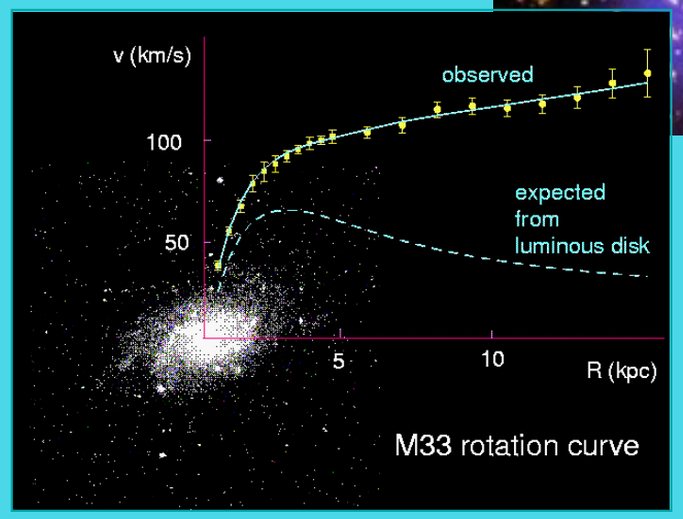

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WIMP = Weakly Interacting Massive Particle

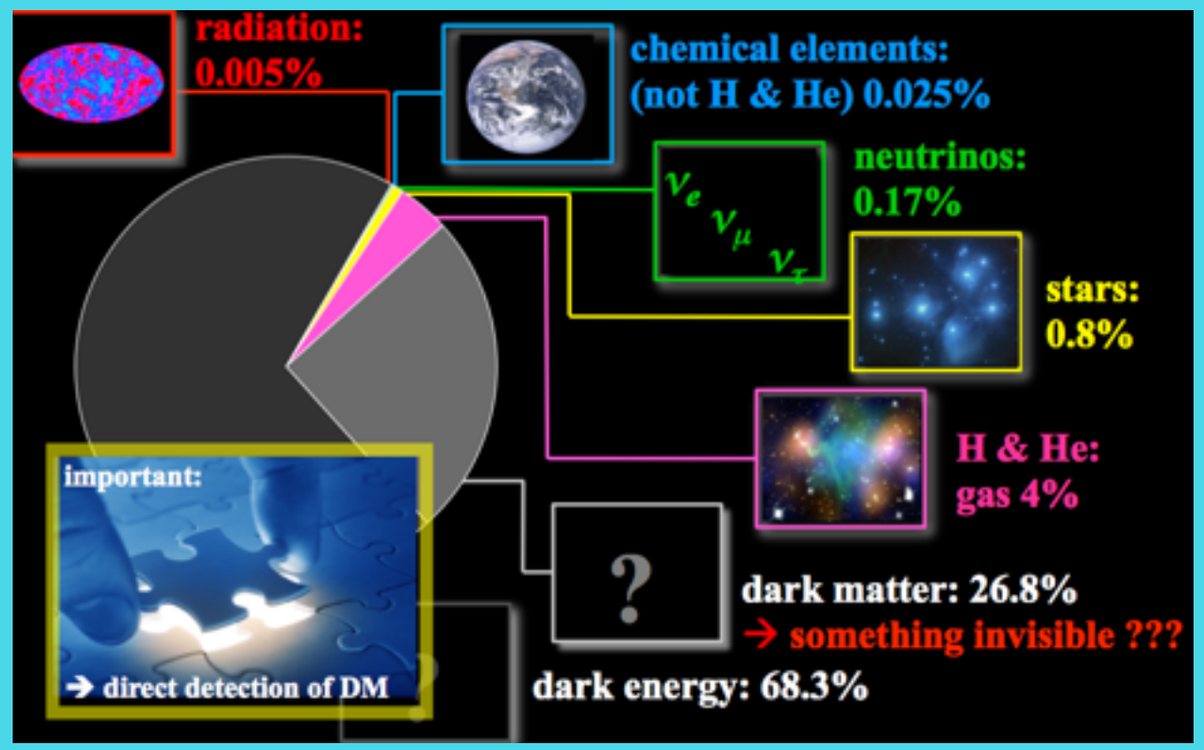
A good argument for new physics at the TeV scale but not fully compelling: DM could well be axions

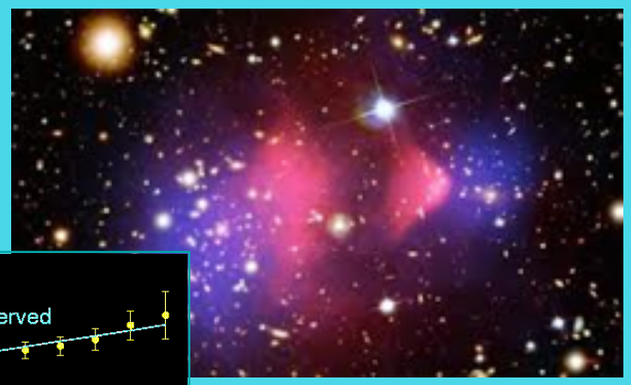
For WIMPs in thermal equilibrium after inflation

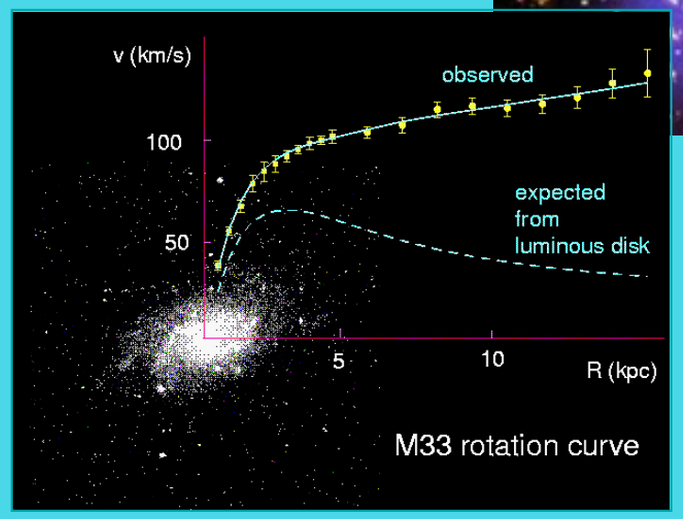
$$\langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

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

Dark Matter







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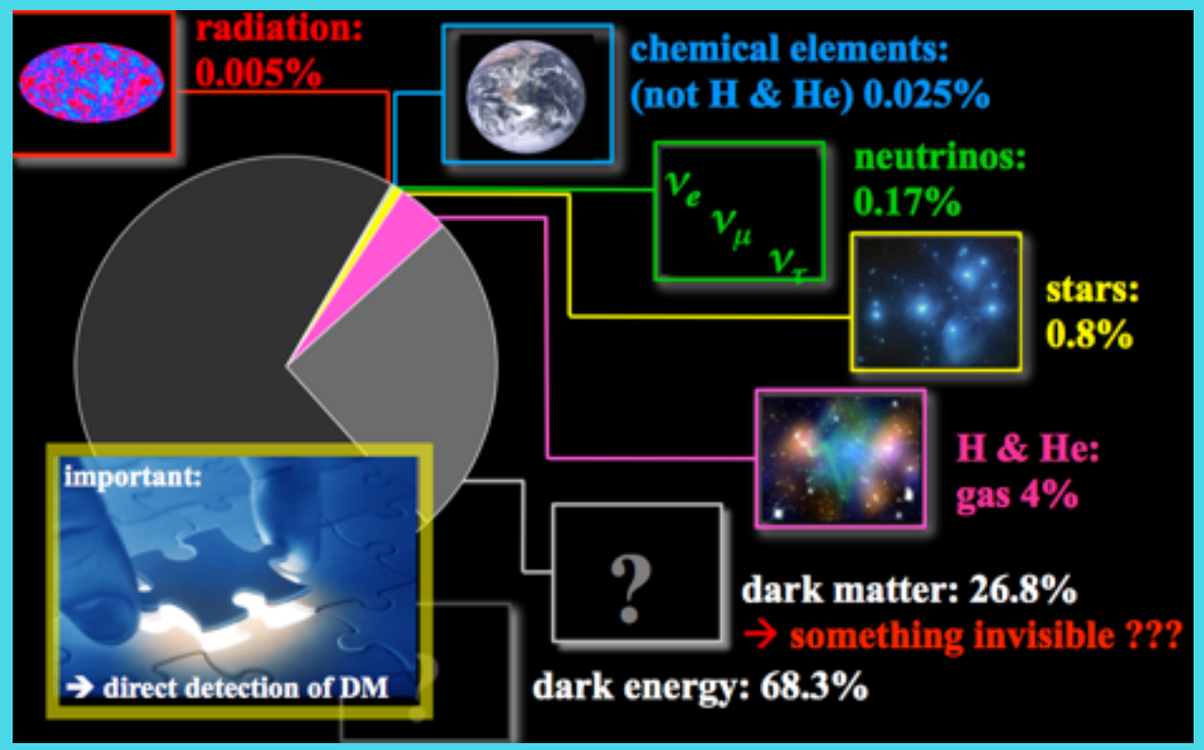

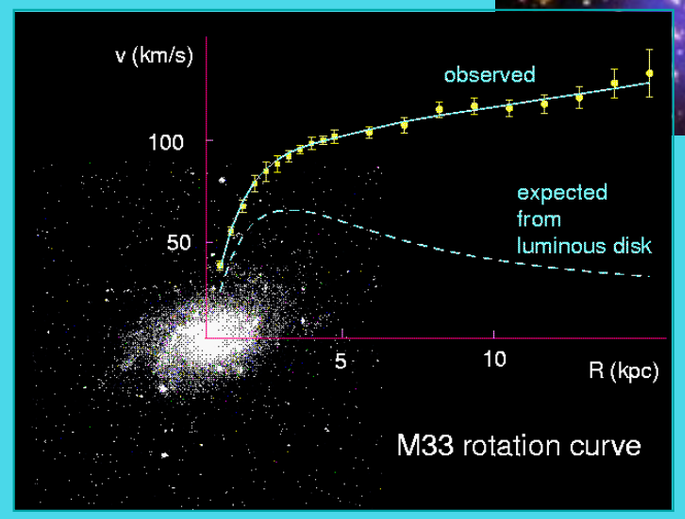

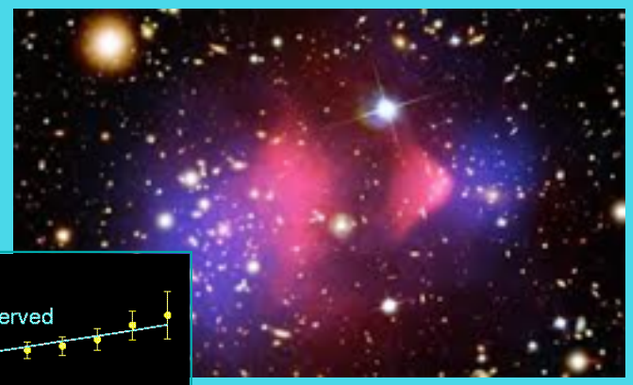

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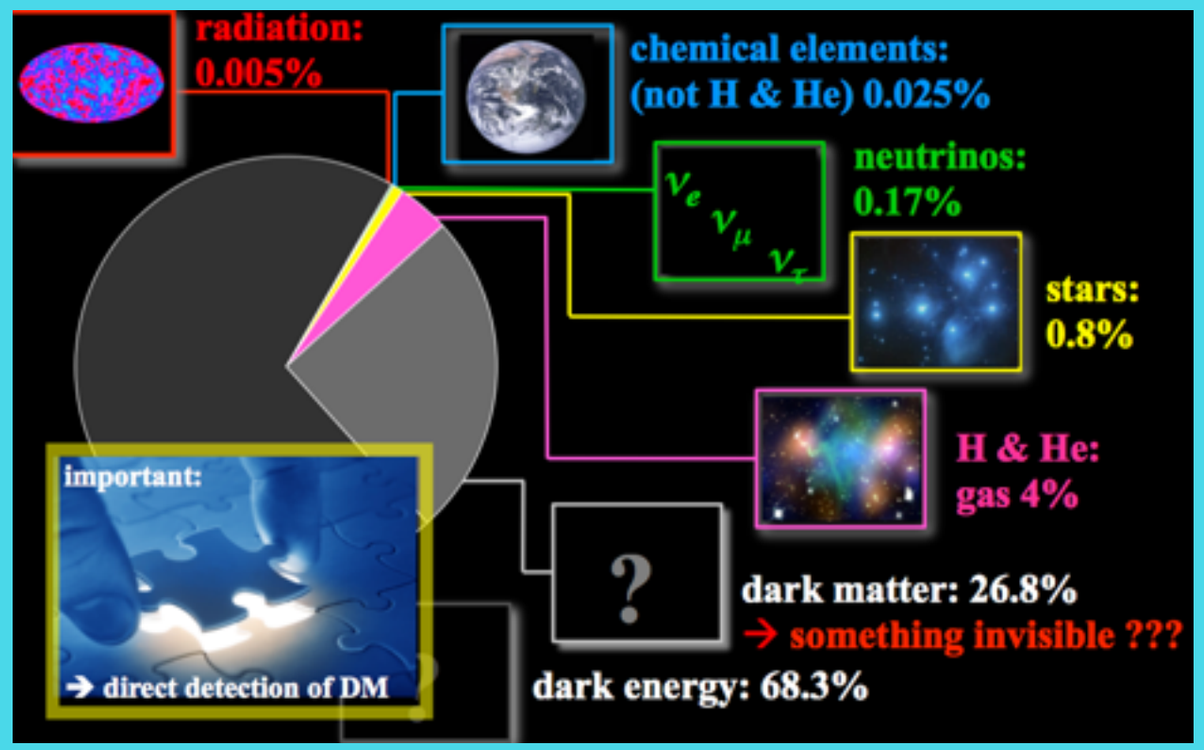

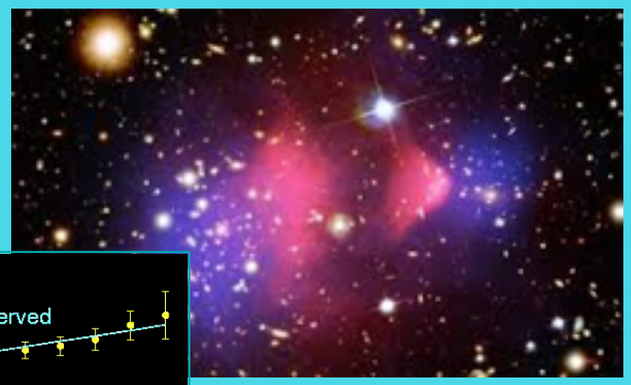

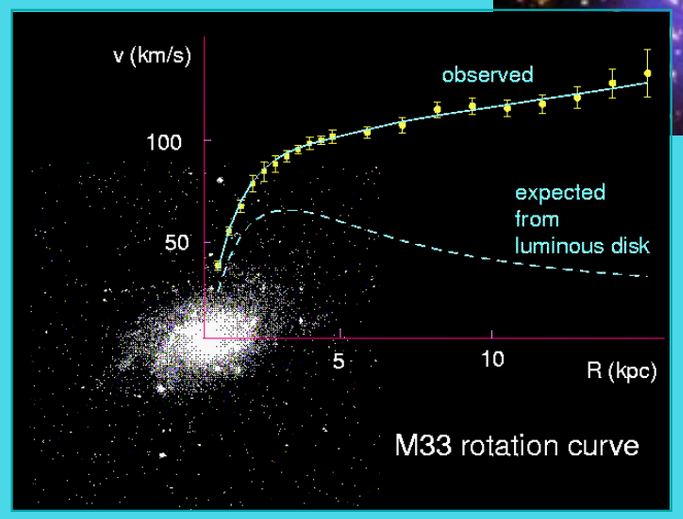

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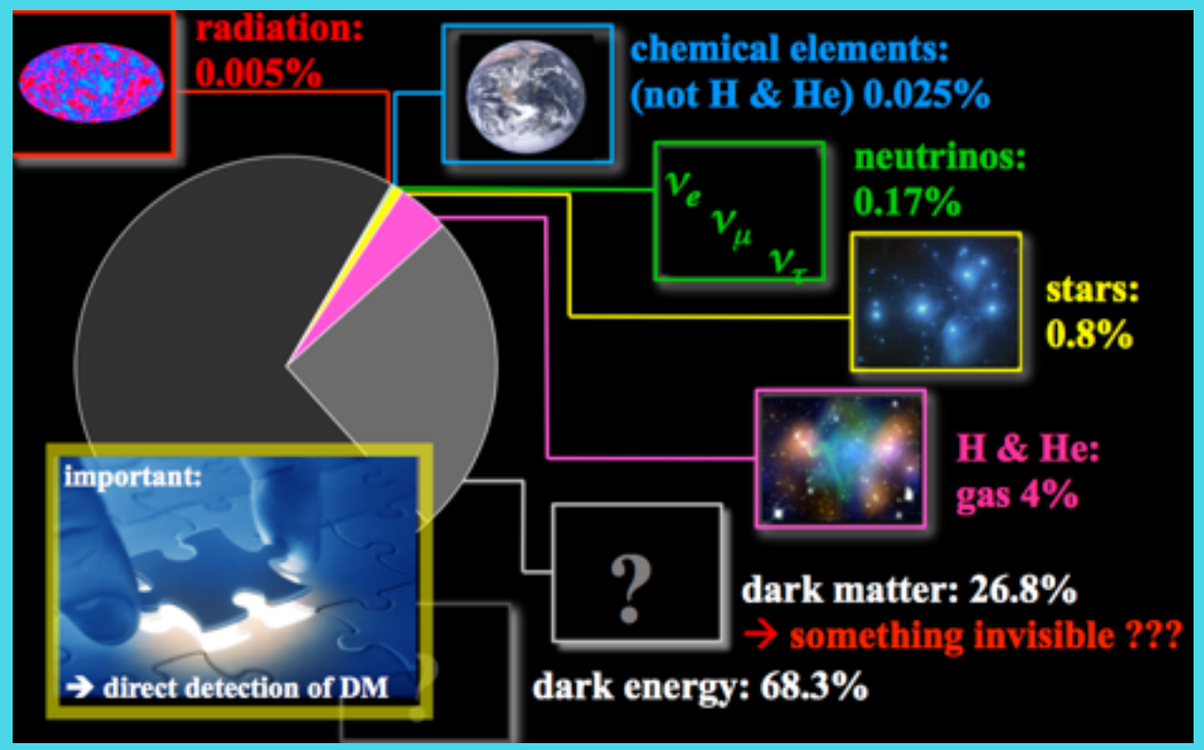

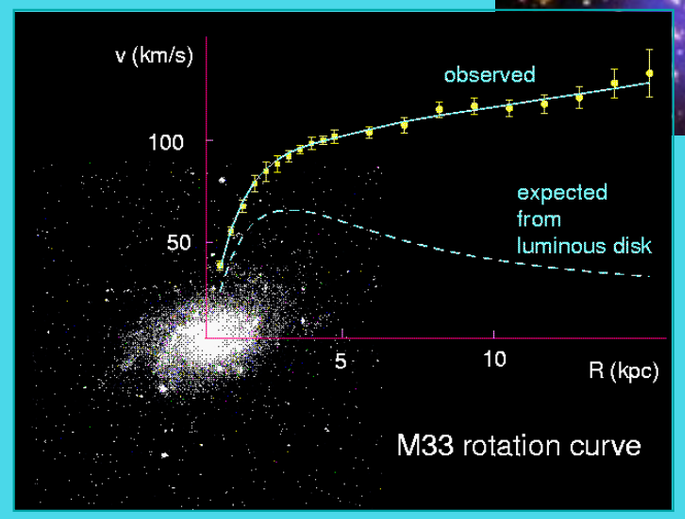

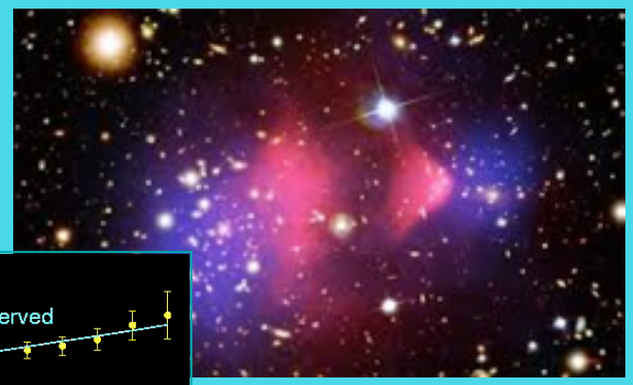

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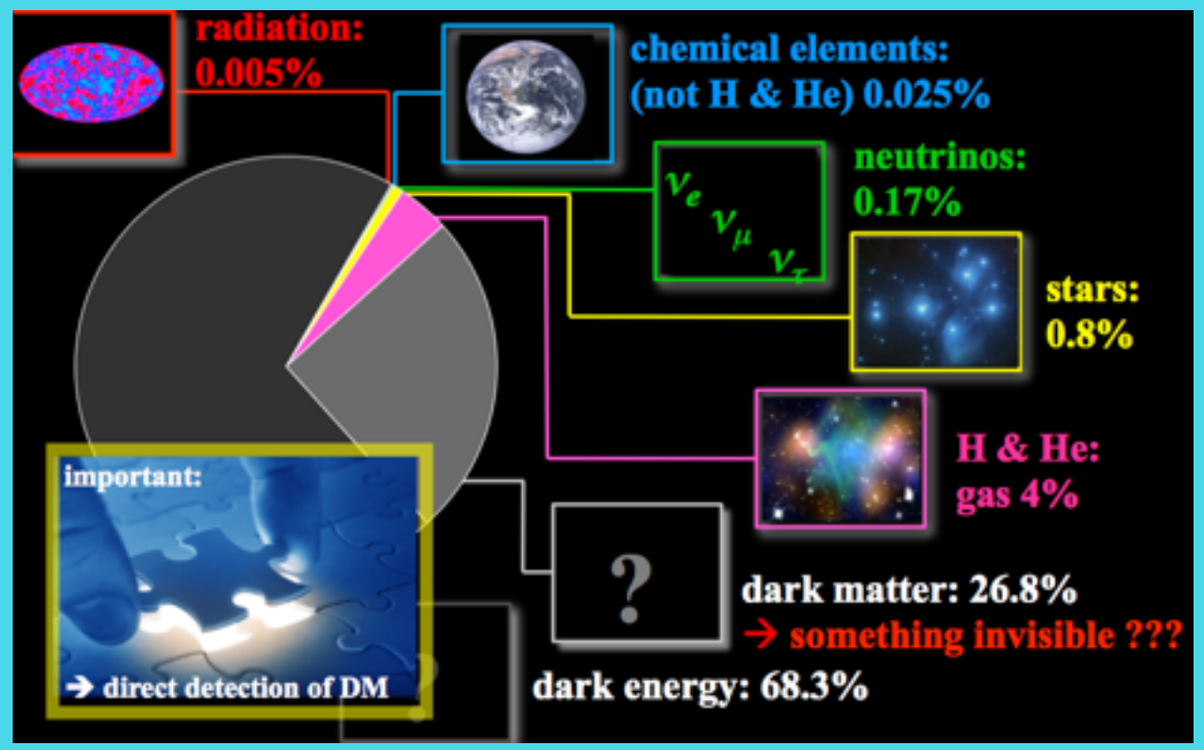

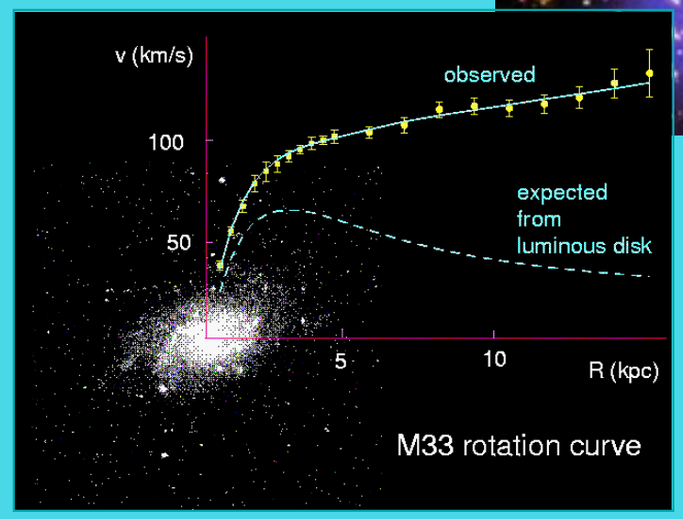

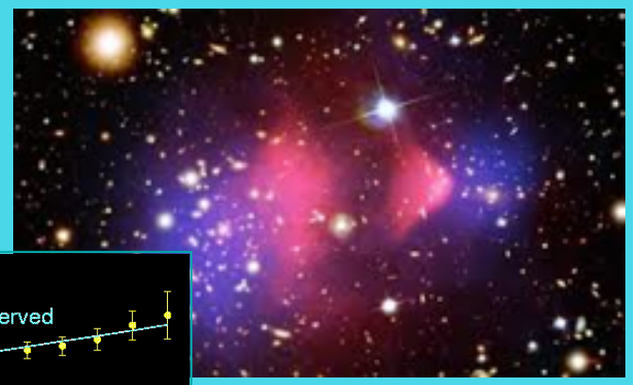

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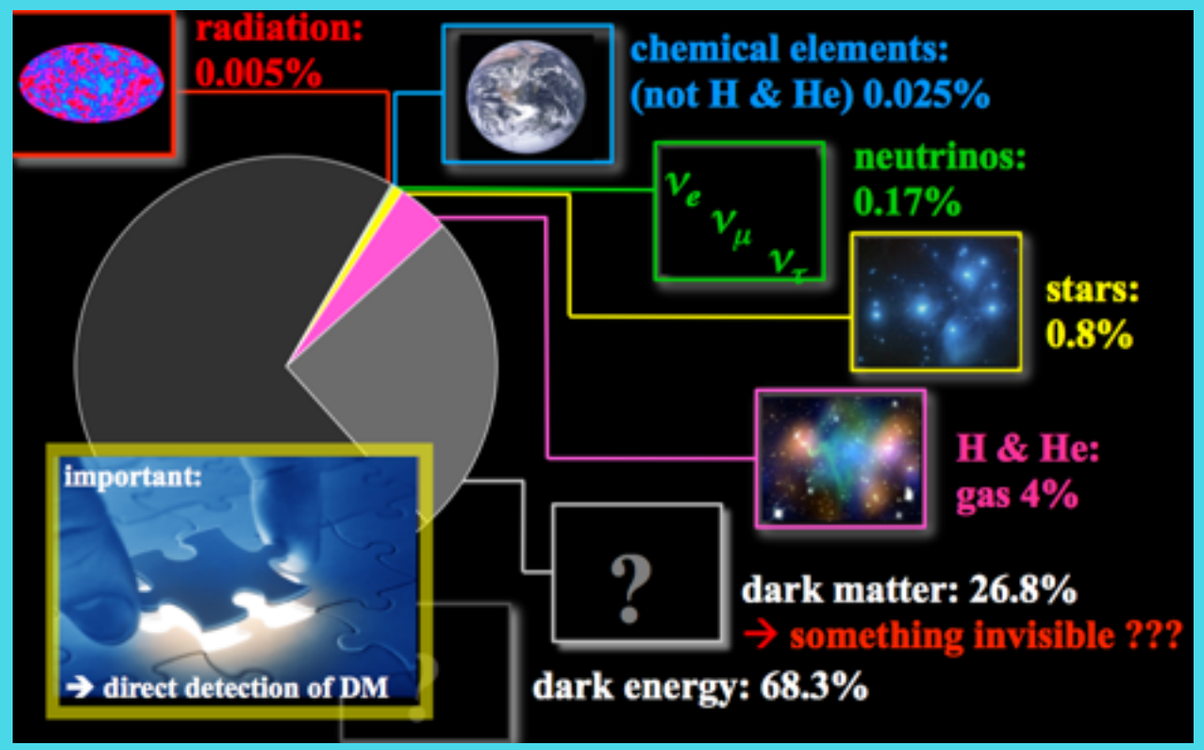

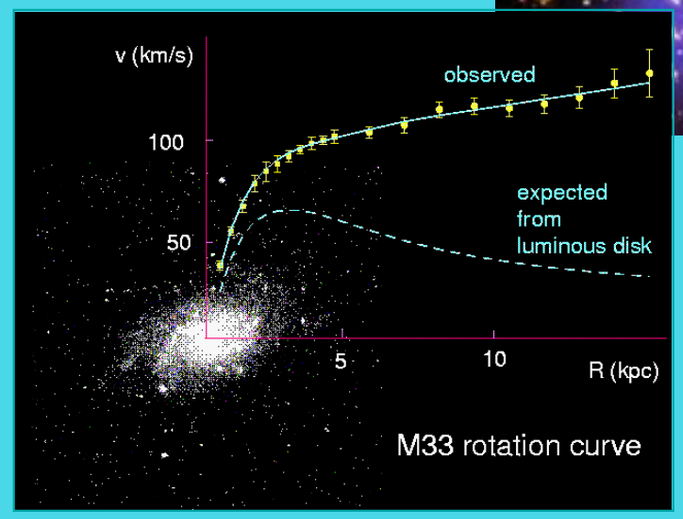

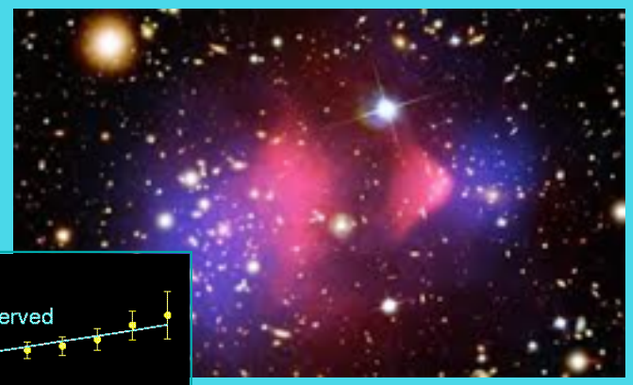

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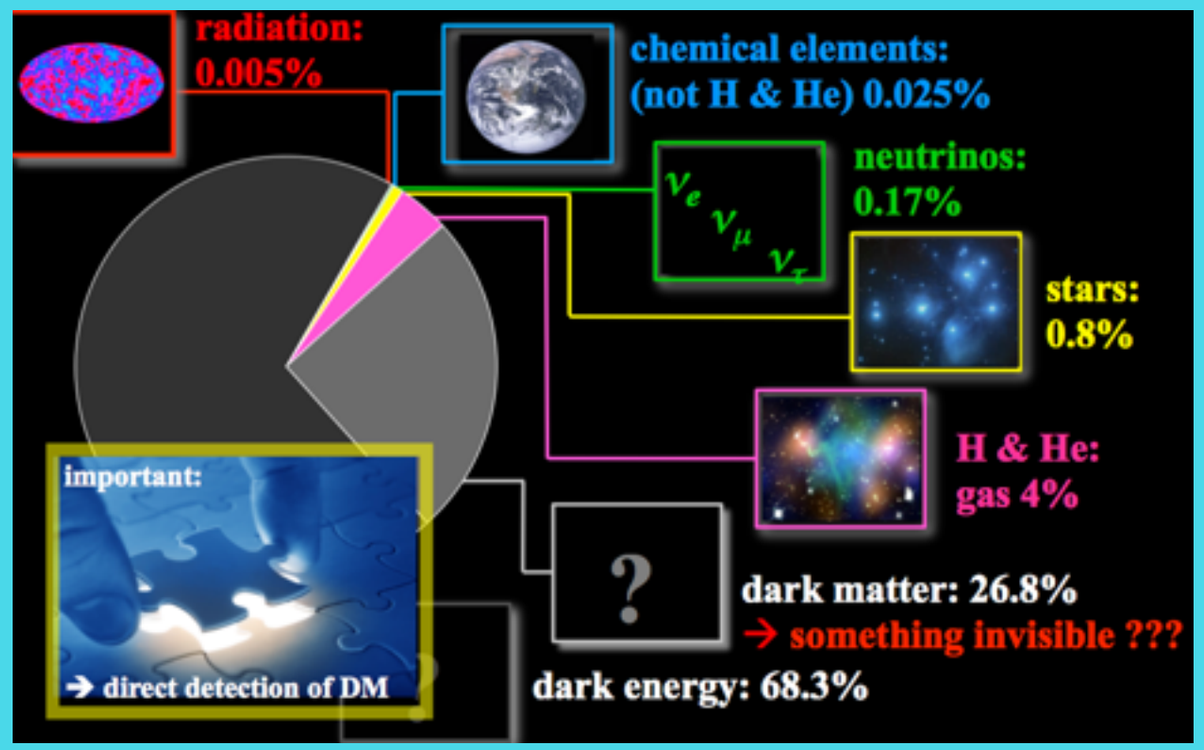

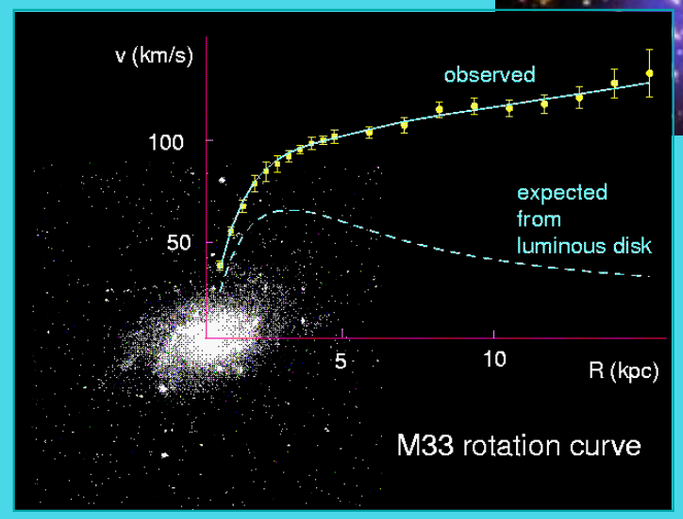

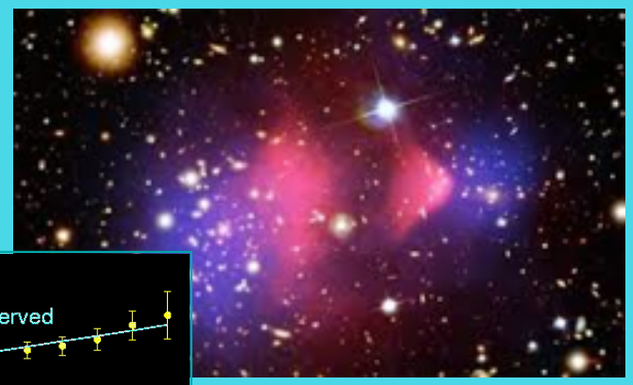

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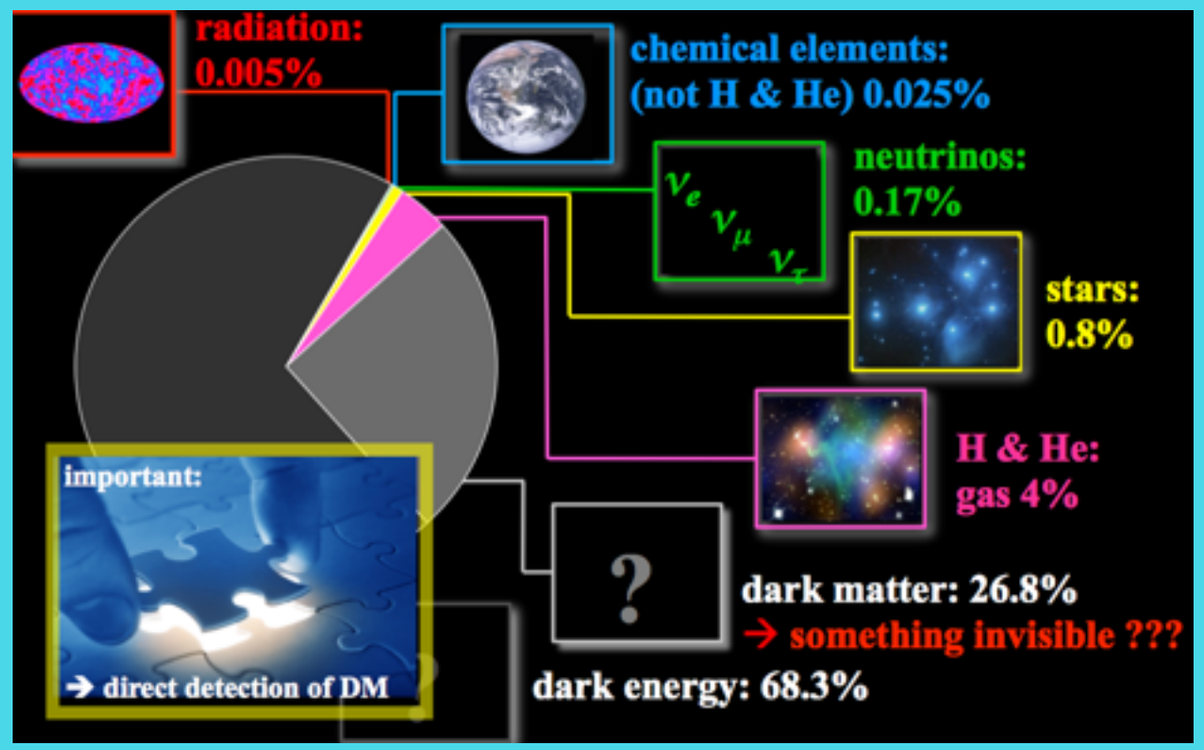

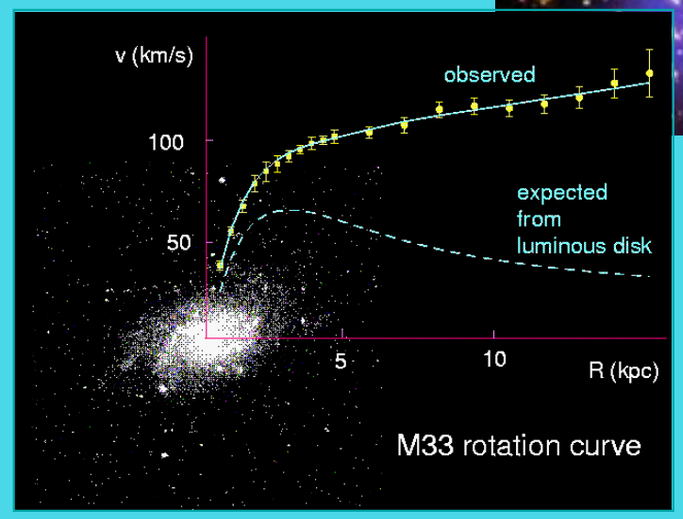

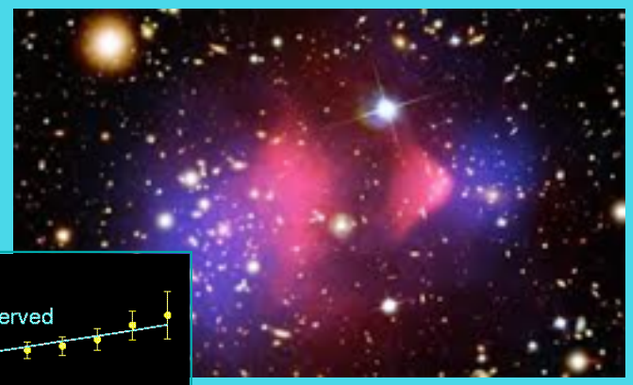

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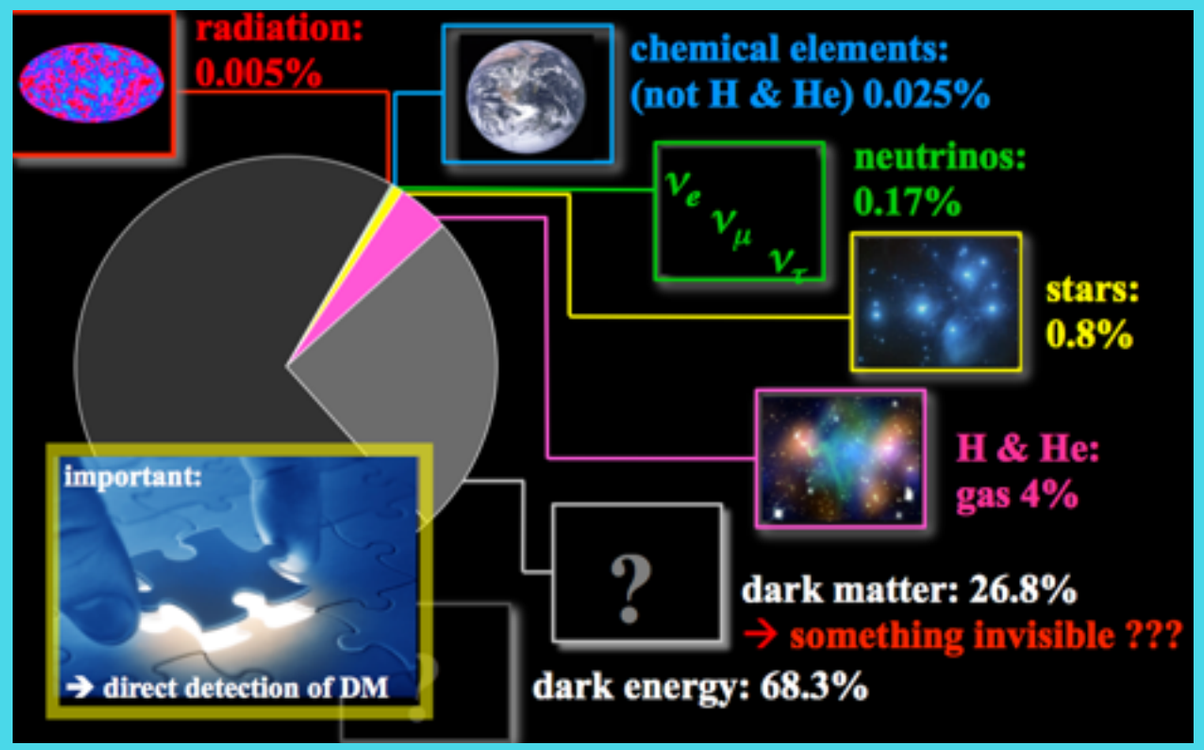

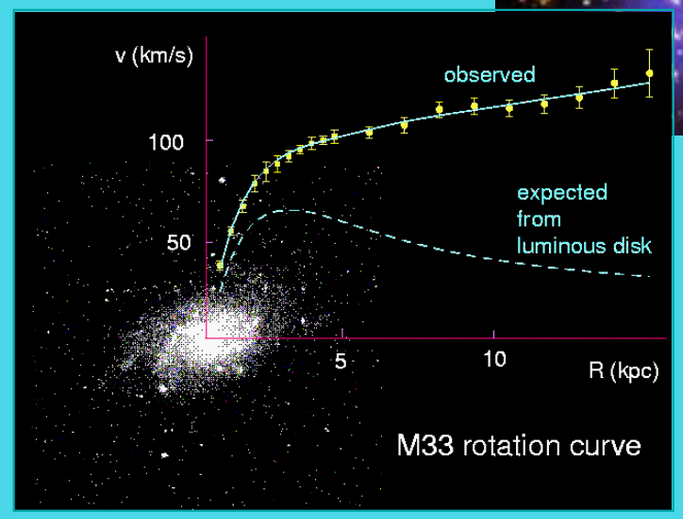

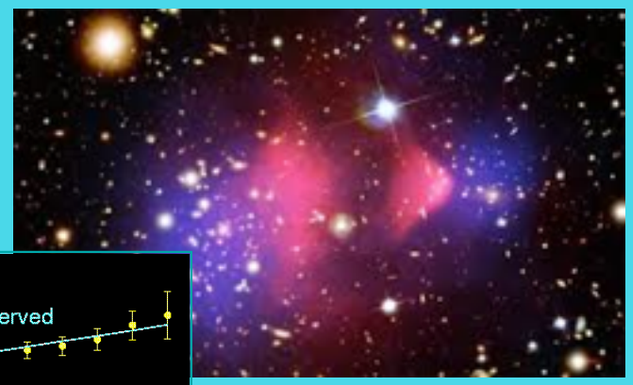

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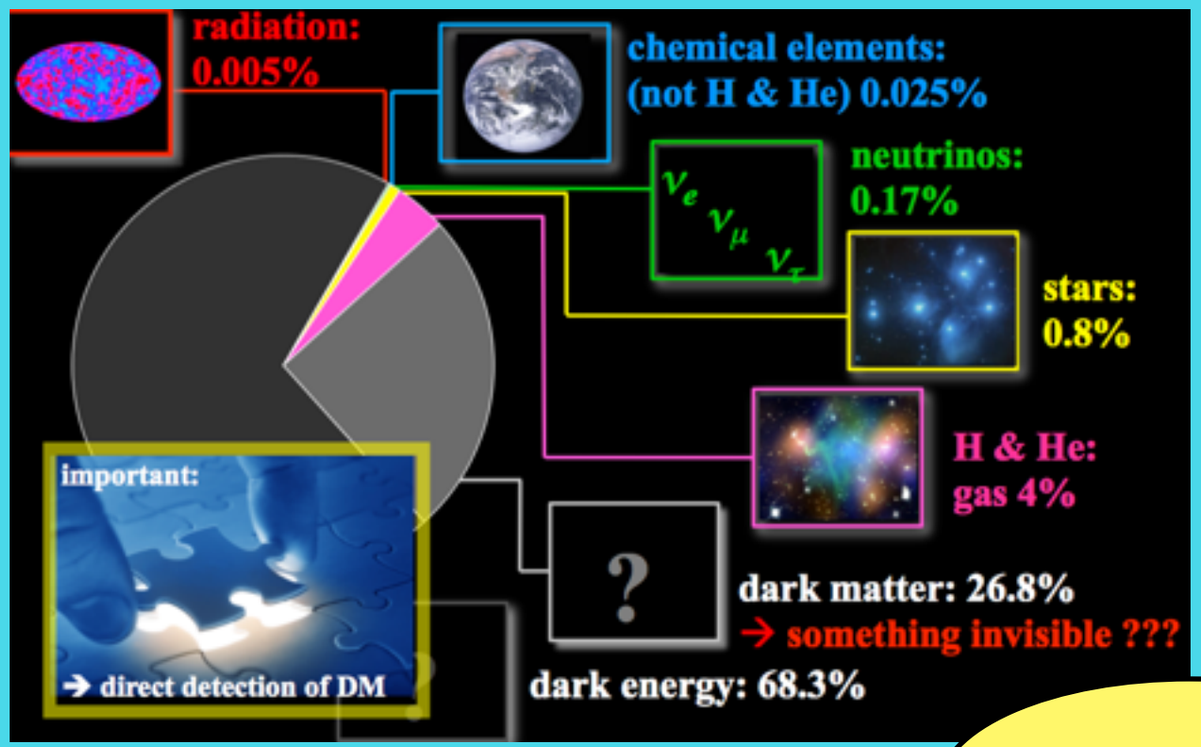

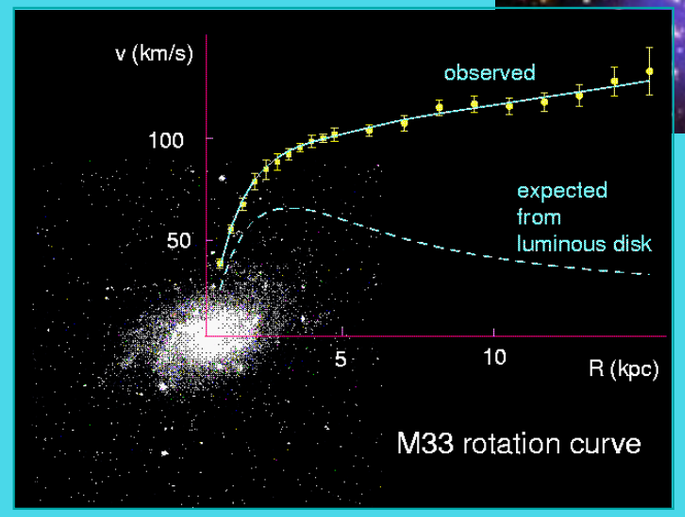

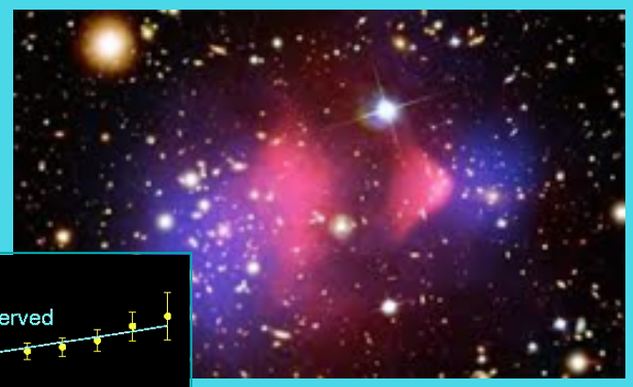

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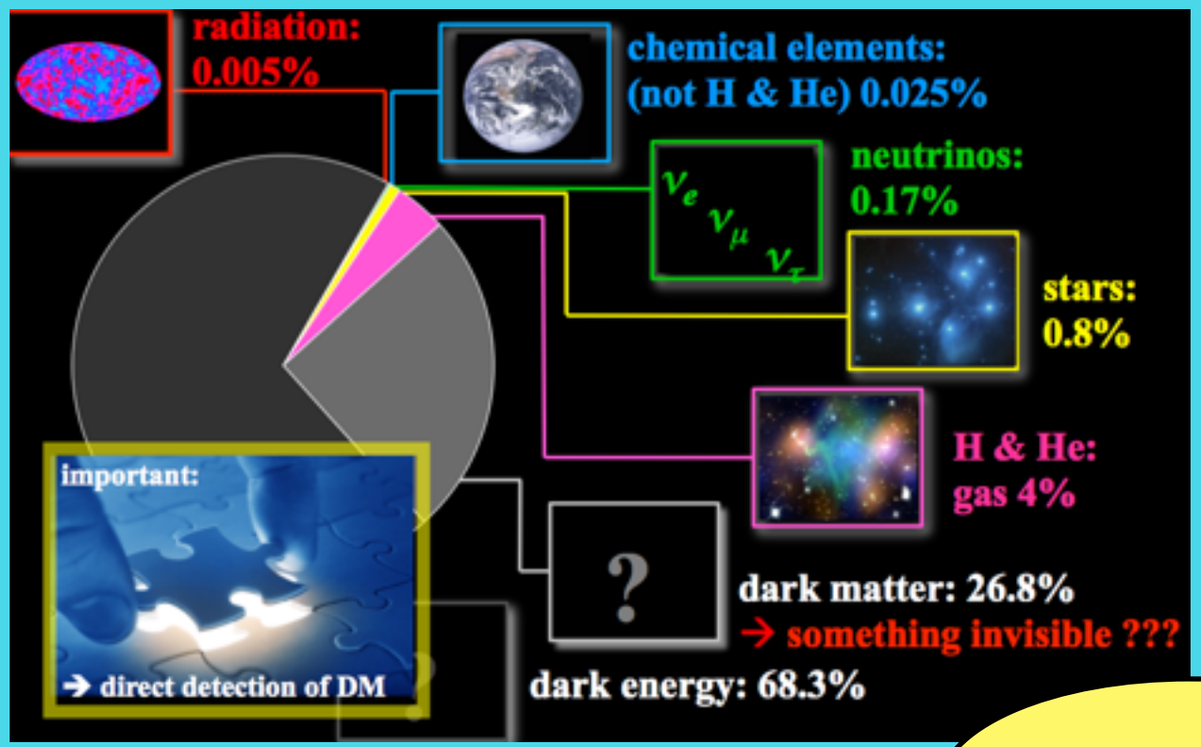

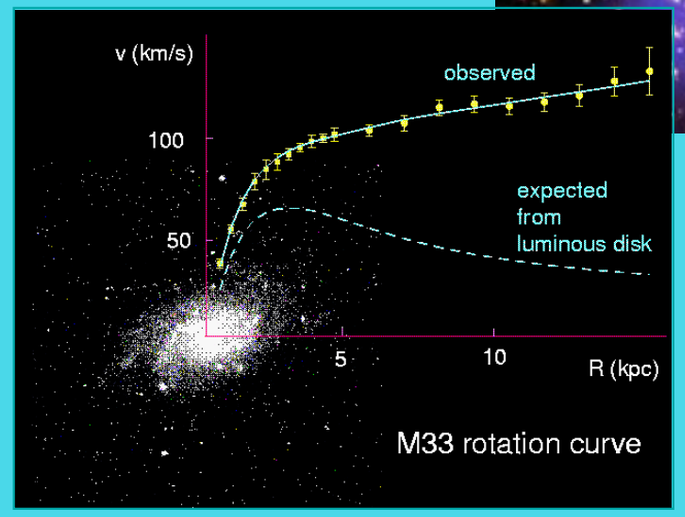

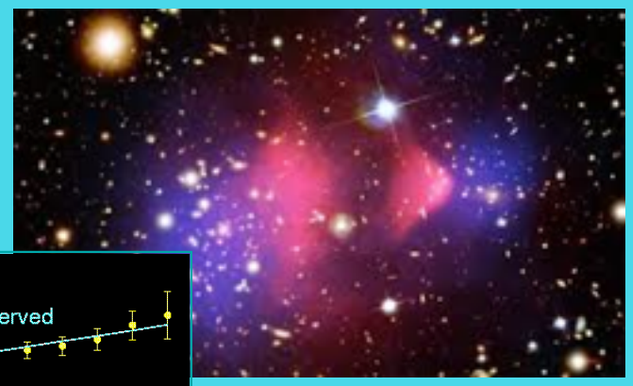

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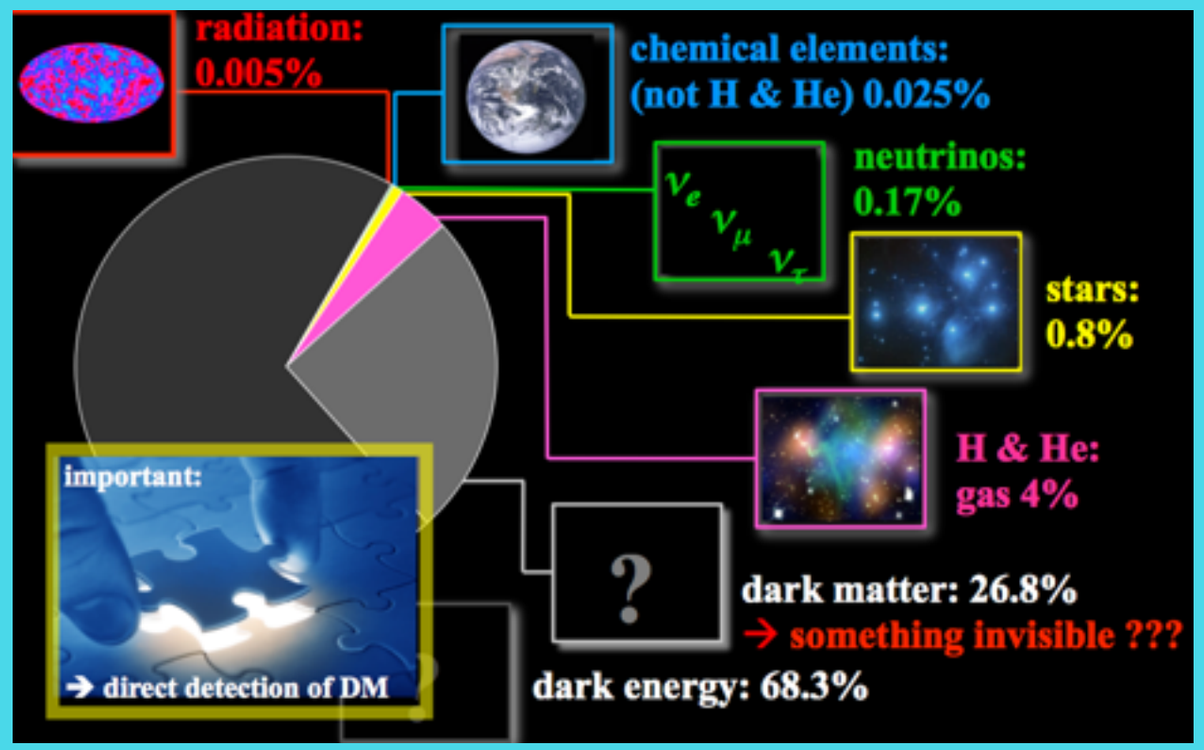
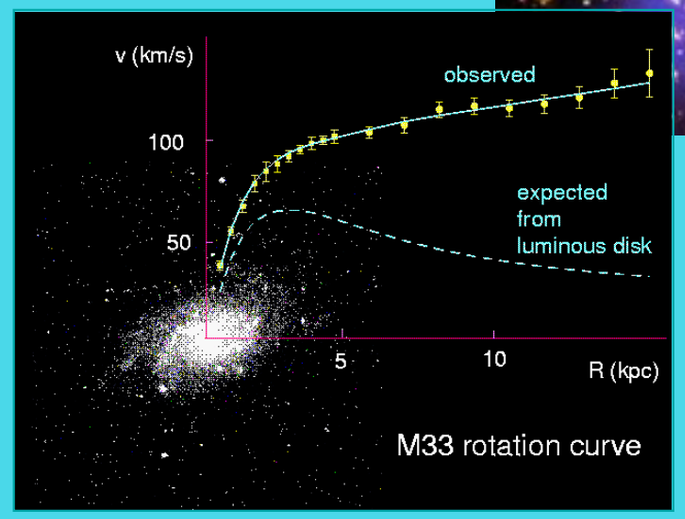
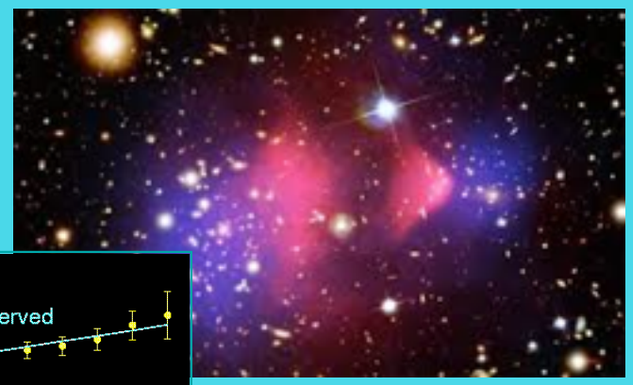
The main candidate in MSSM

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

- right-handed neutrino
- neutralino
- sneutrino
- axion (axino)
- gravitino
- heavy photon
- light sterile Higgs

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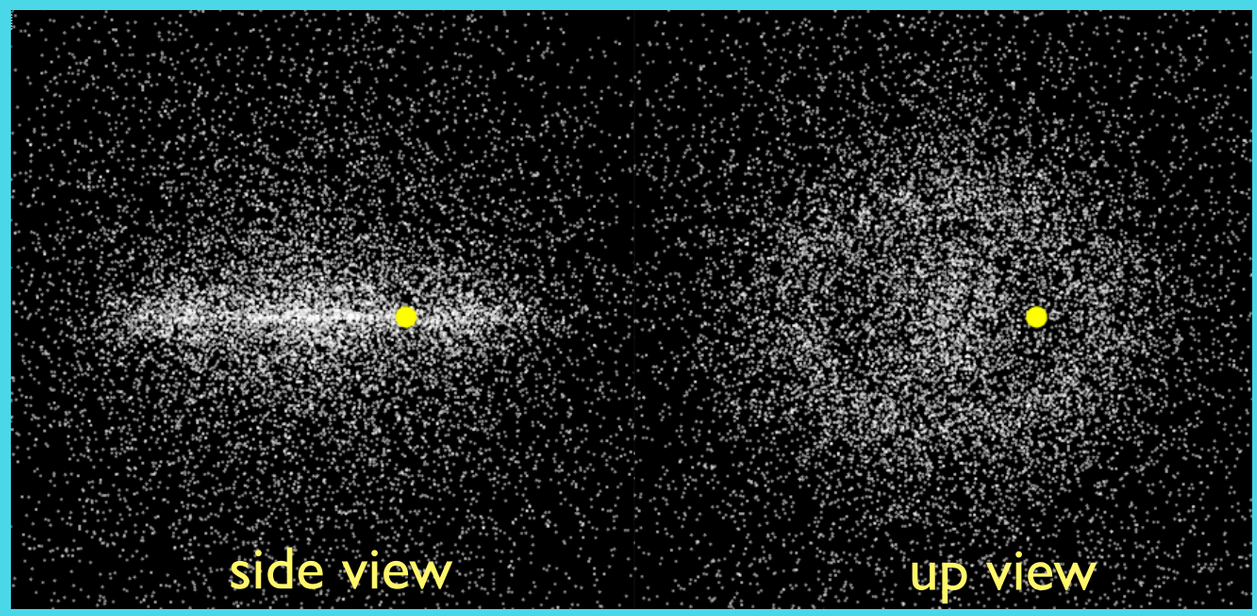
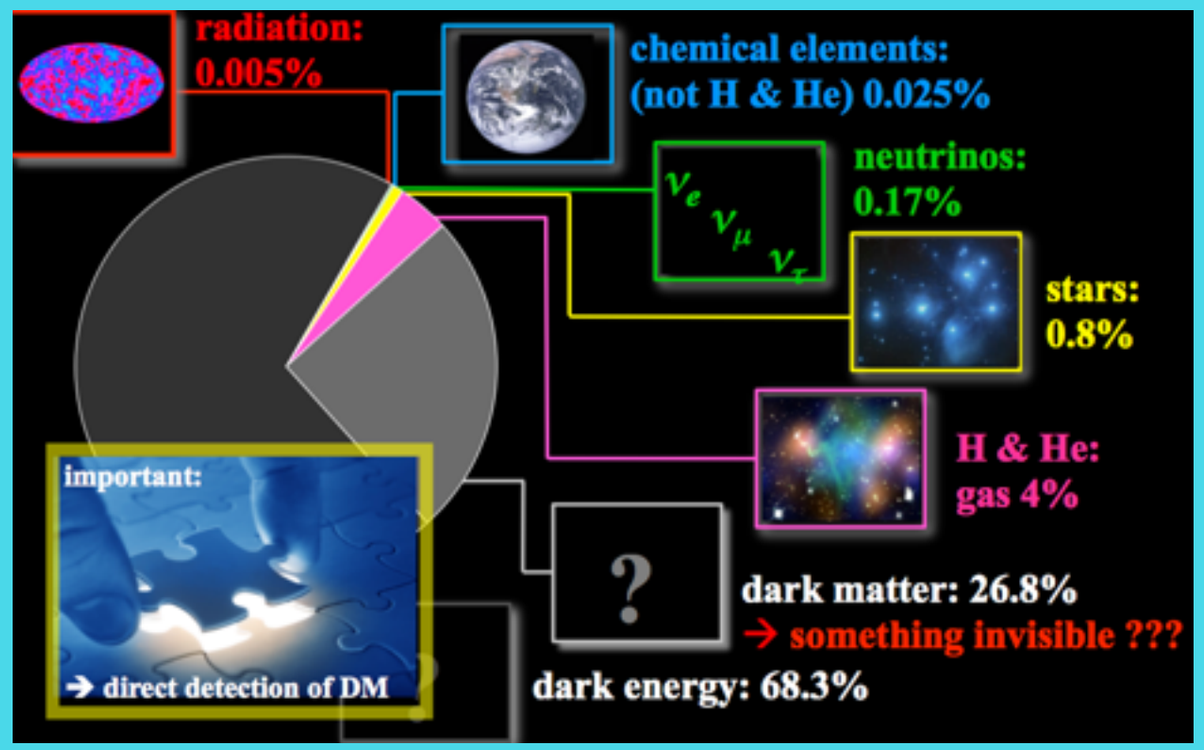
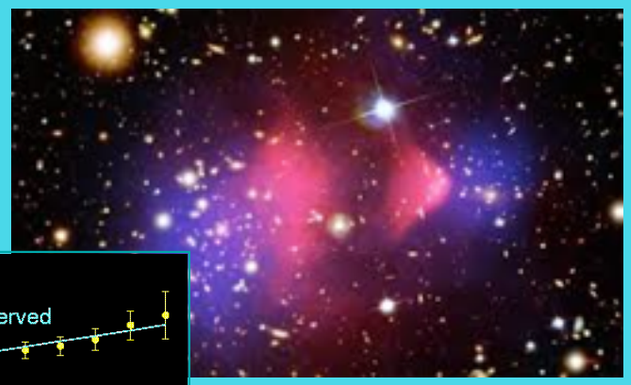
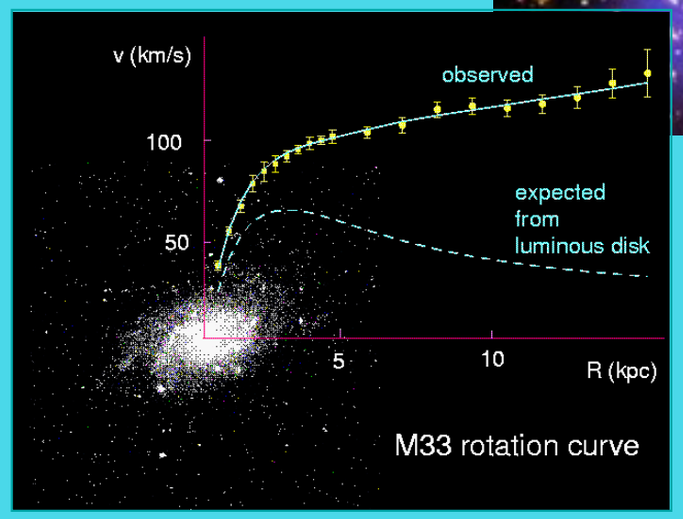


The structure of the DM halo in Milky Way

Dark Matter







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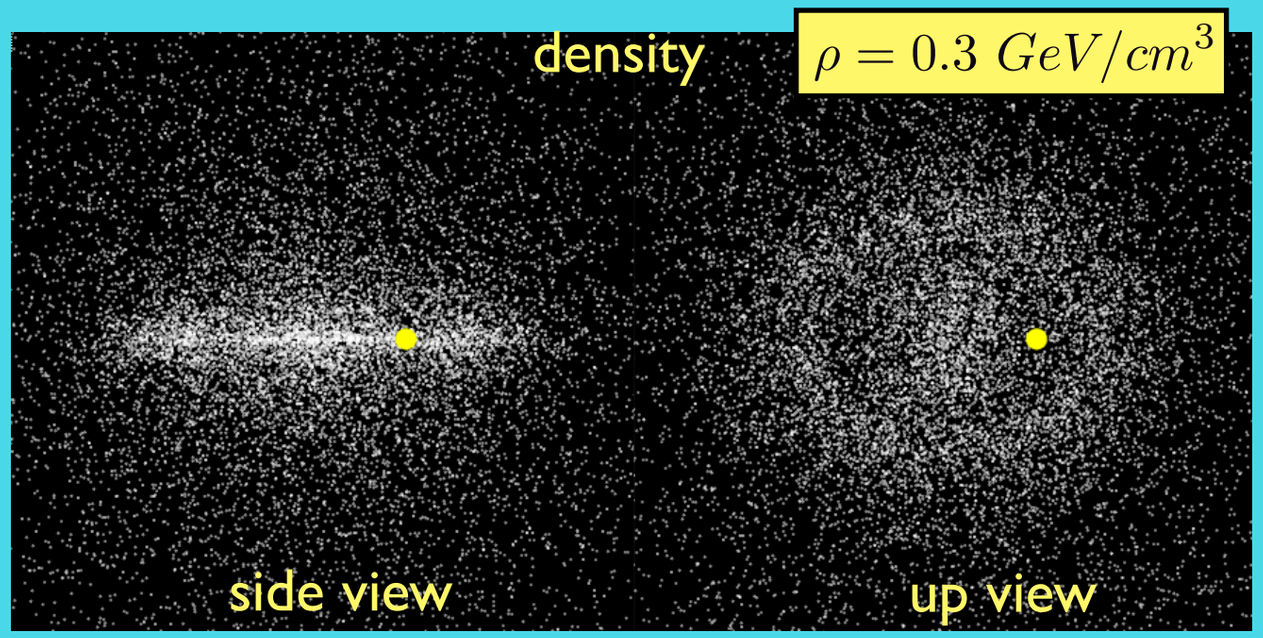
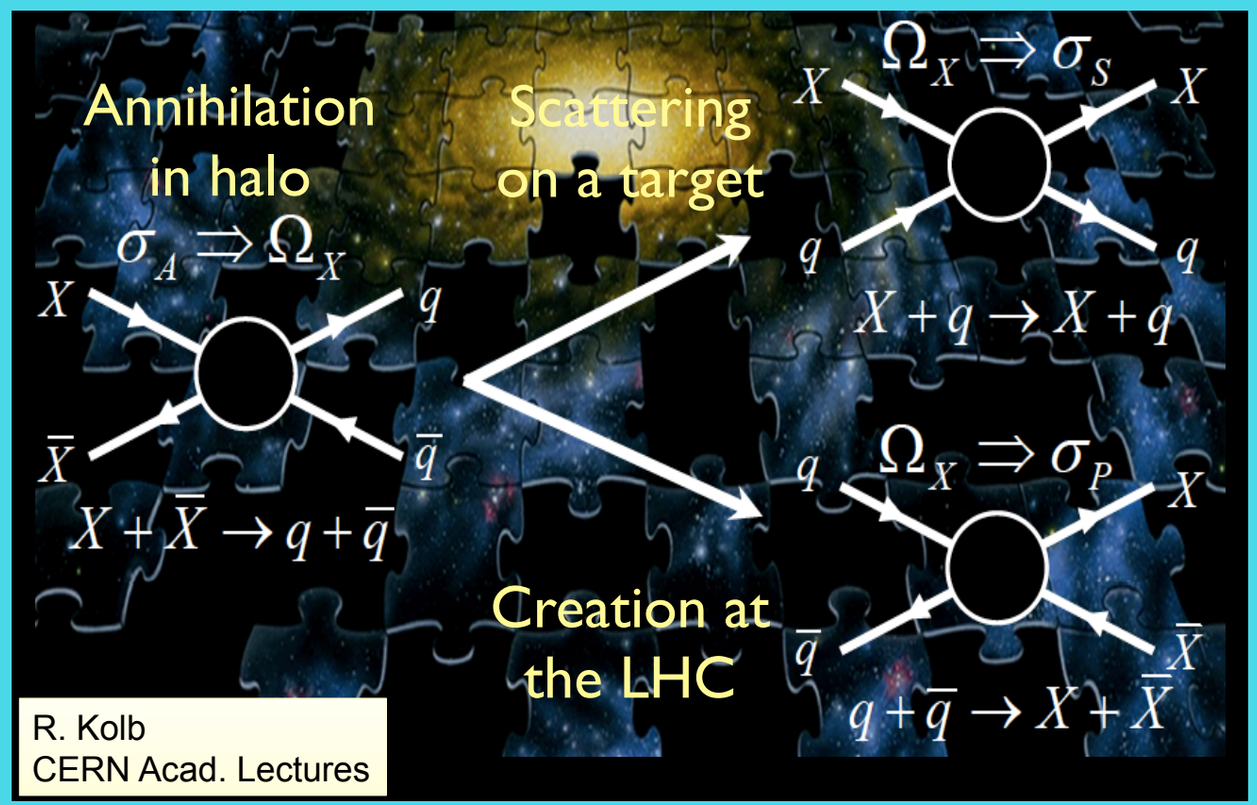


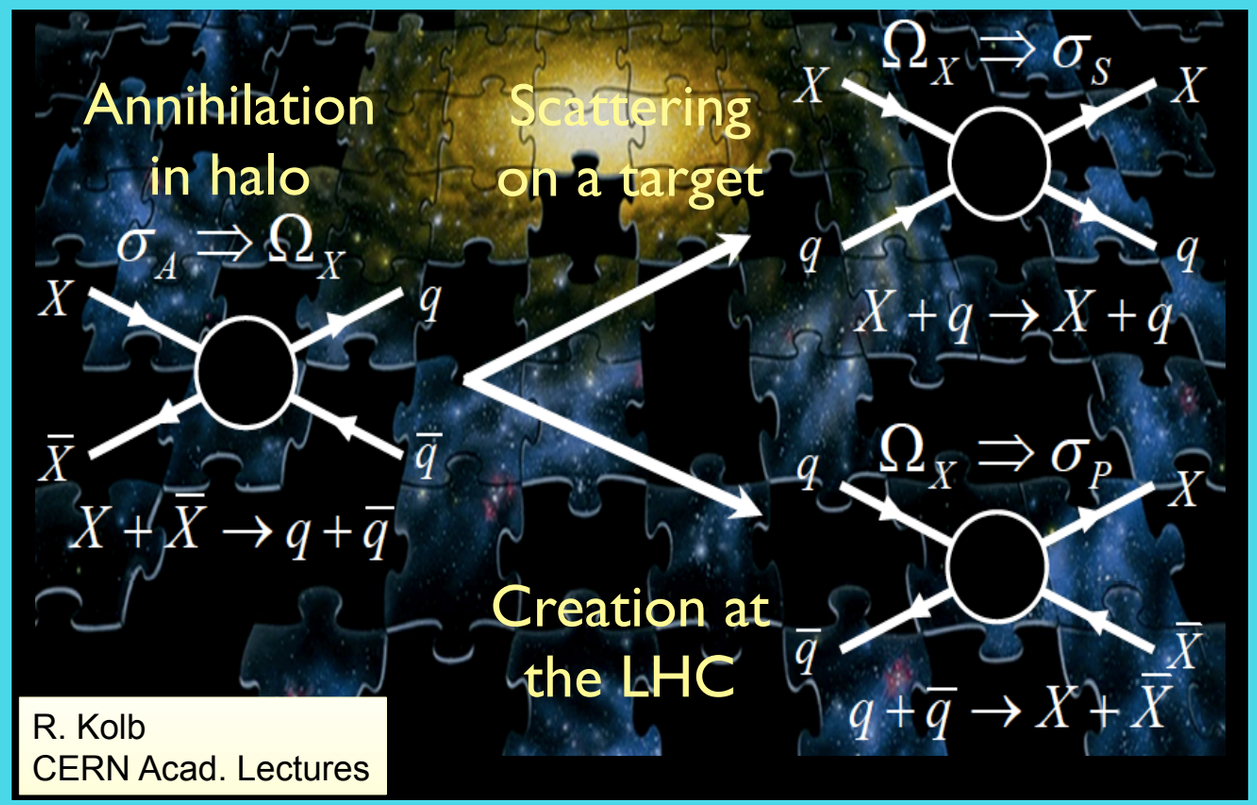
The structure of the DM halo in Milky Way

Search for the Dark Matter

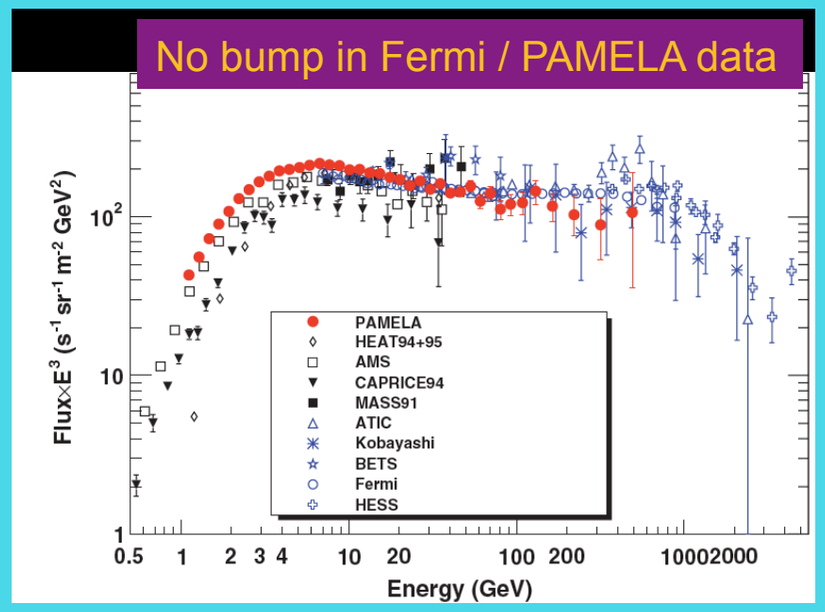


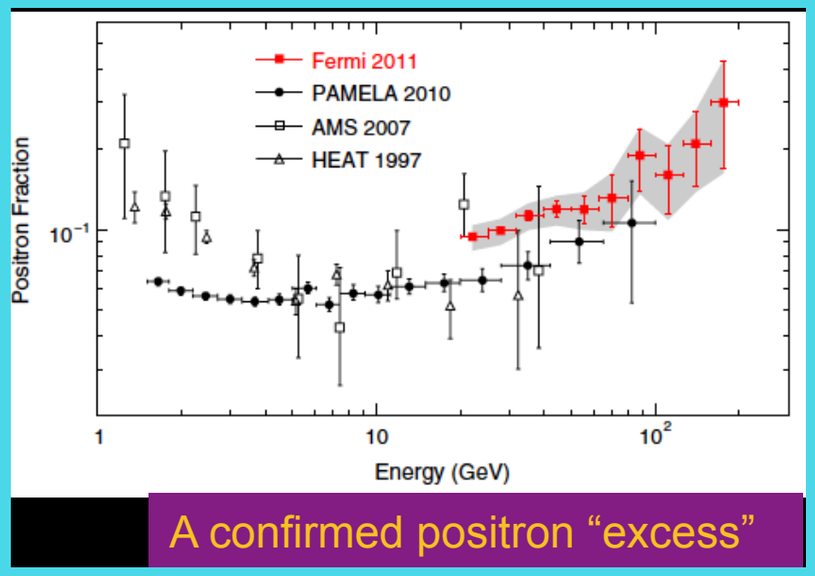
R. Kolb
CERN Acad. Lectures

Search for the Dark Matter



Annihilation
in halo





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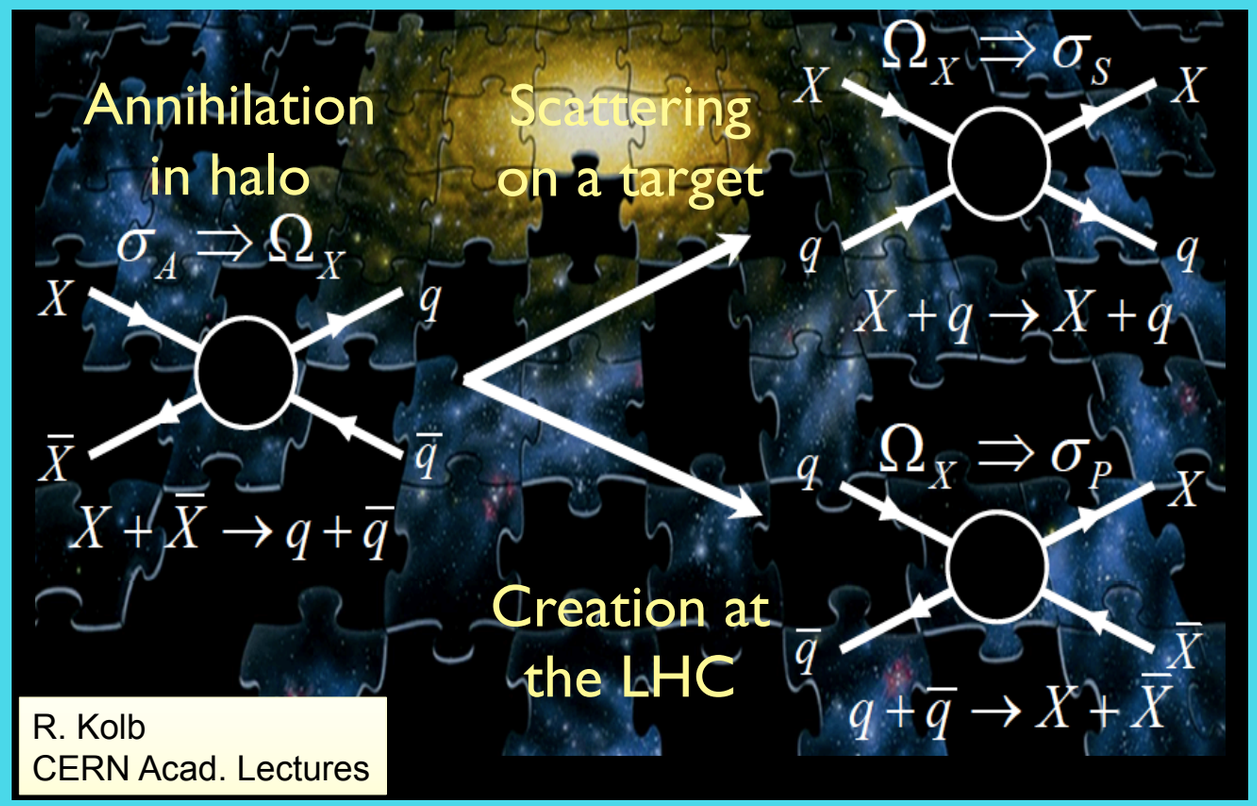
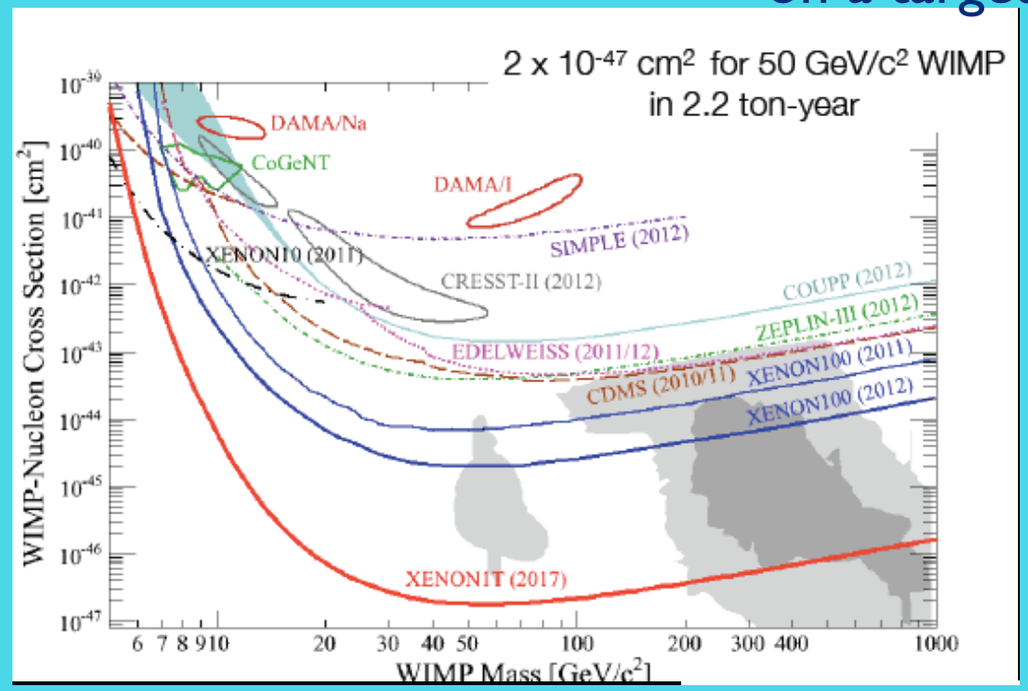


Scattering
on a target



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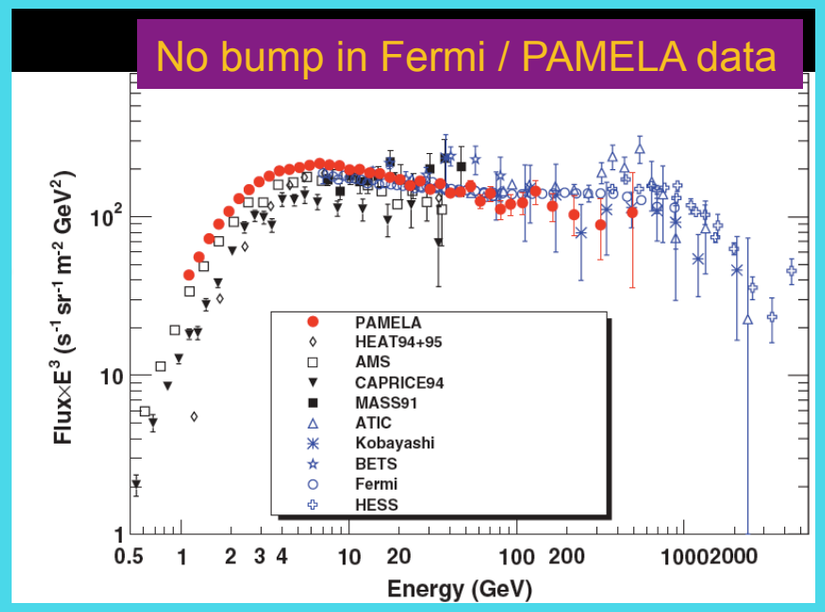

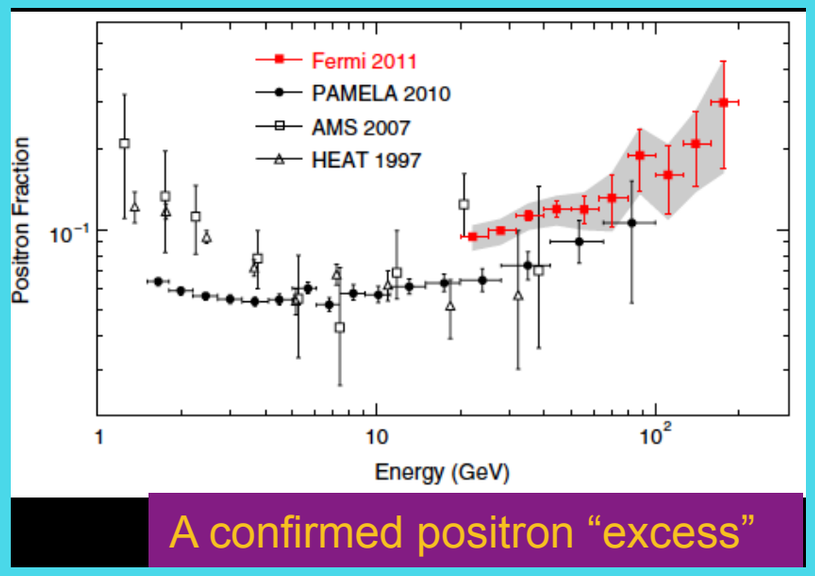

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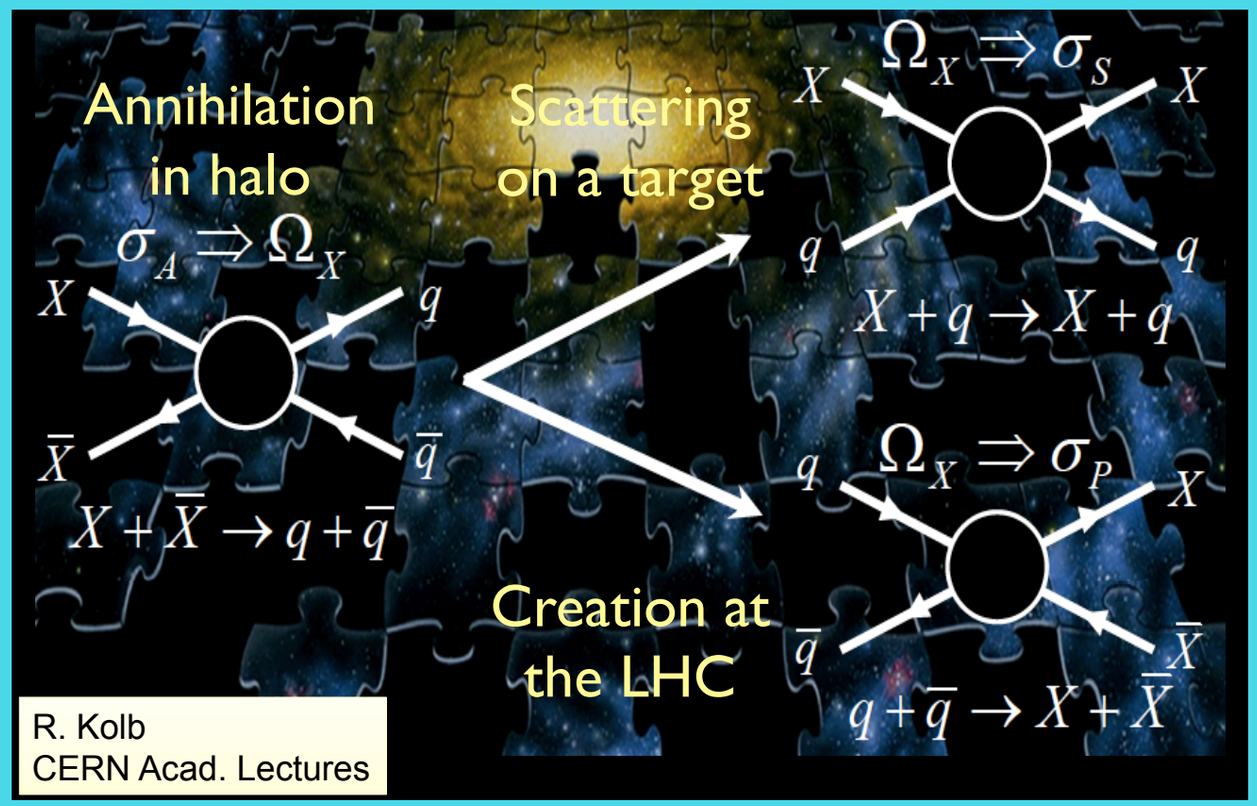

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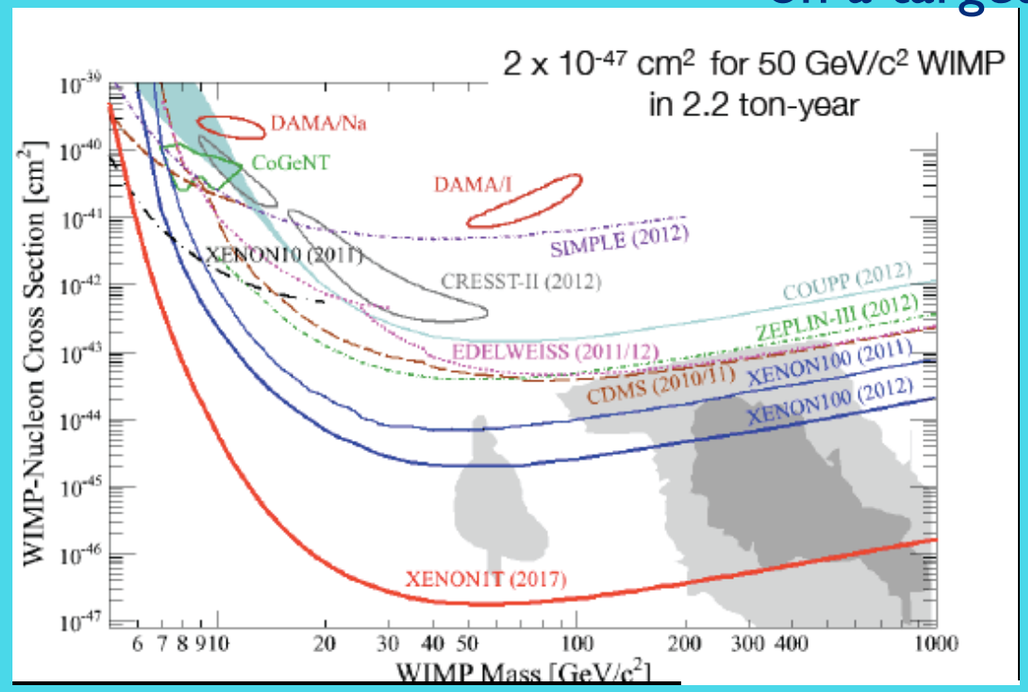
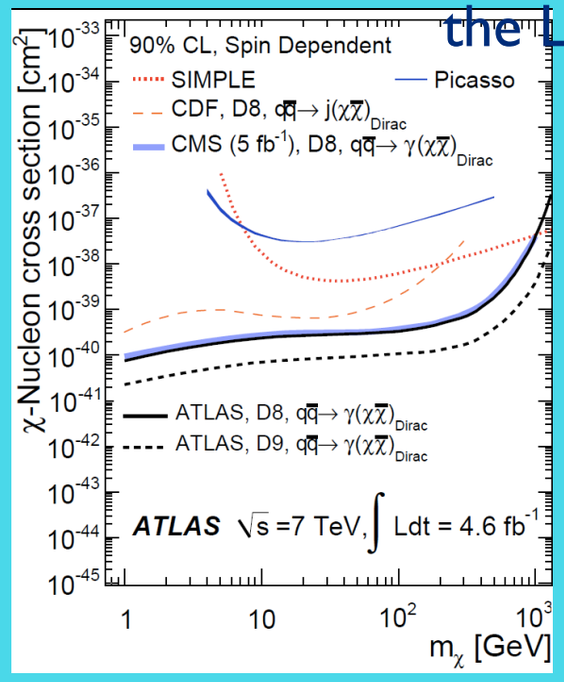
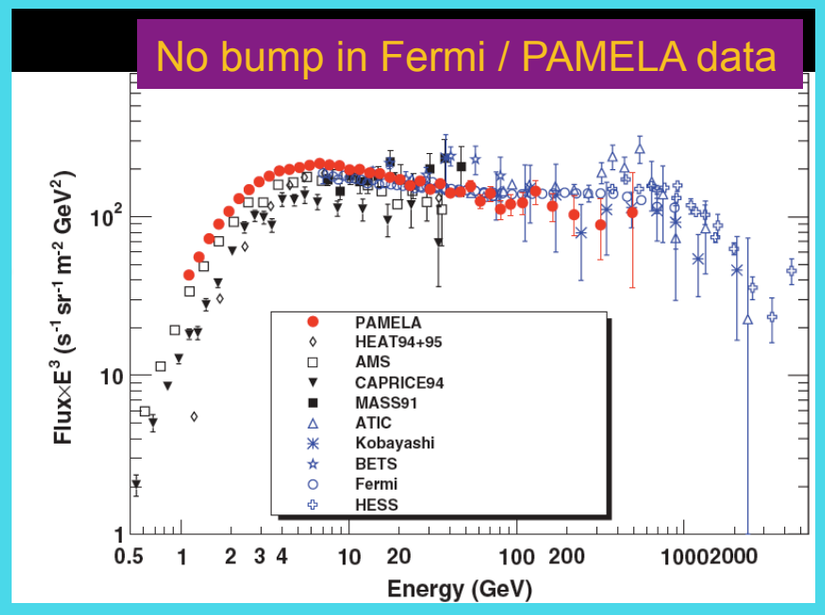


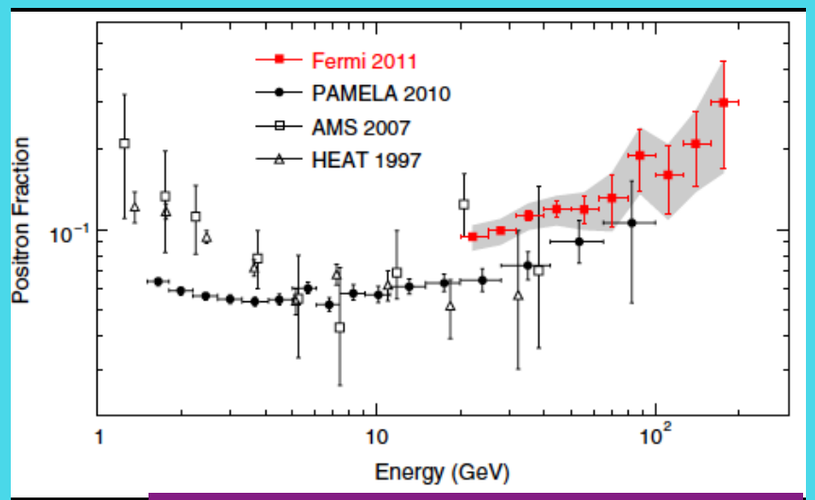
Annihilation in halo

Creation at the LHC



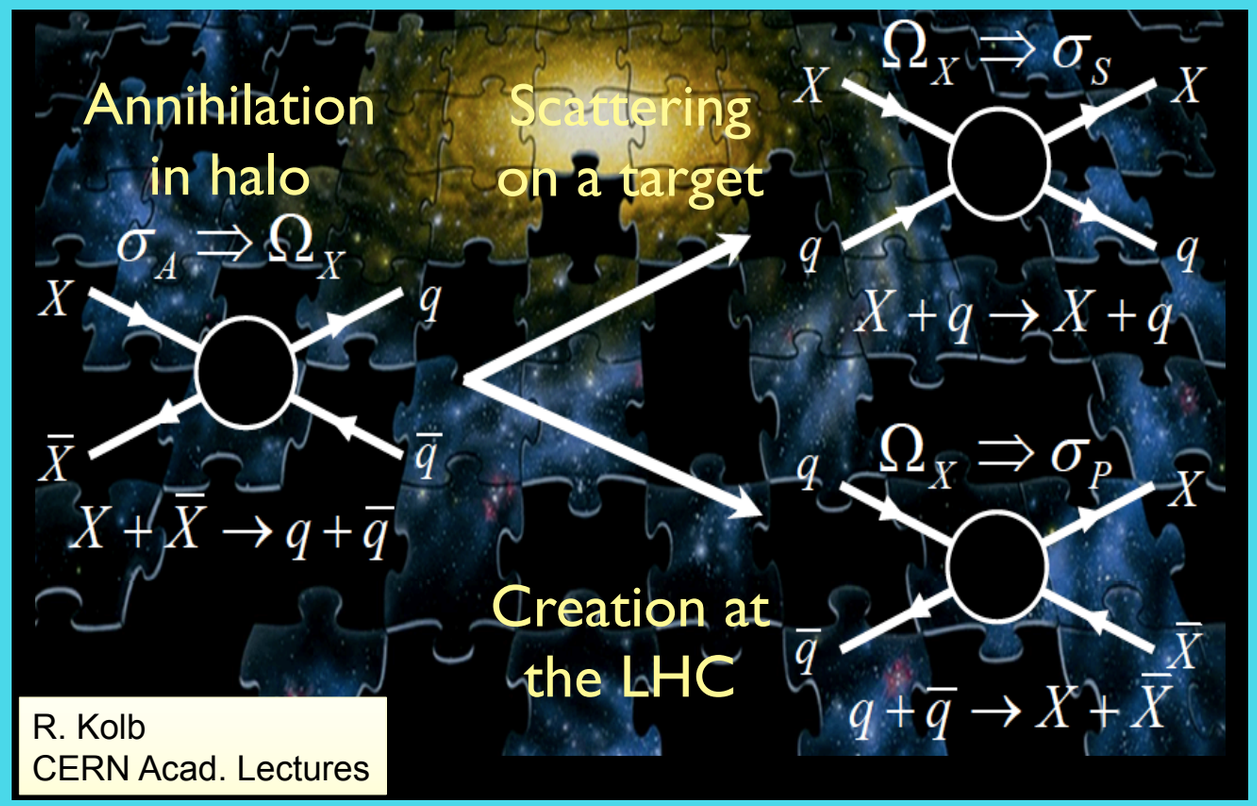
No bump in Fermi / PAMELA data





A confirmed positron “excess”

Search for the Dark Matter



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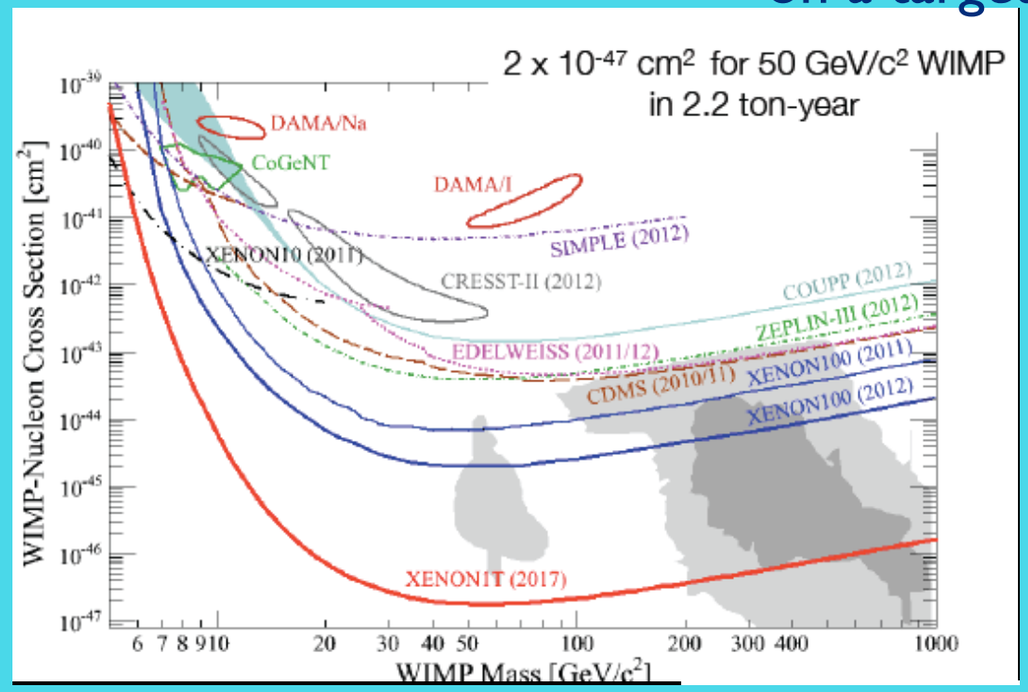

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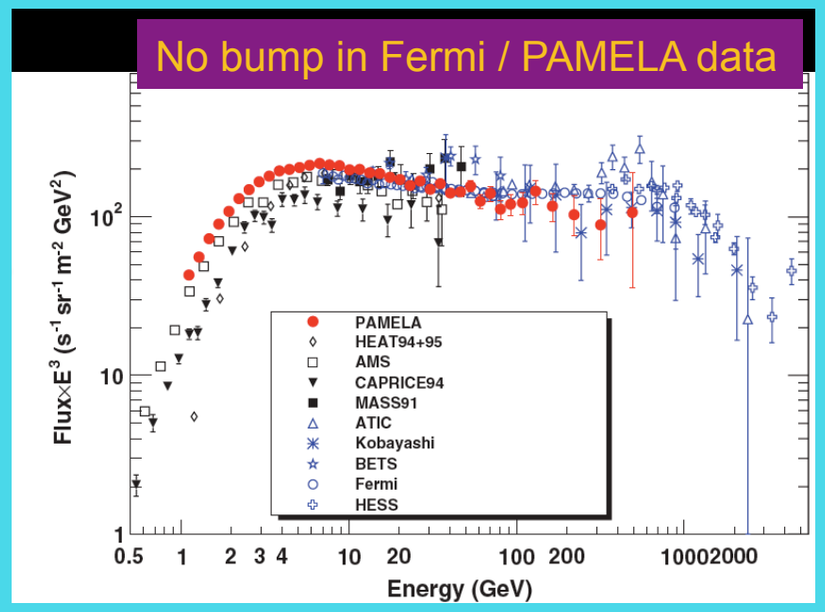

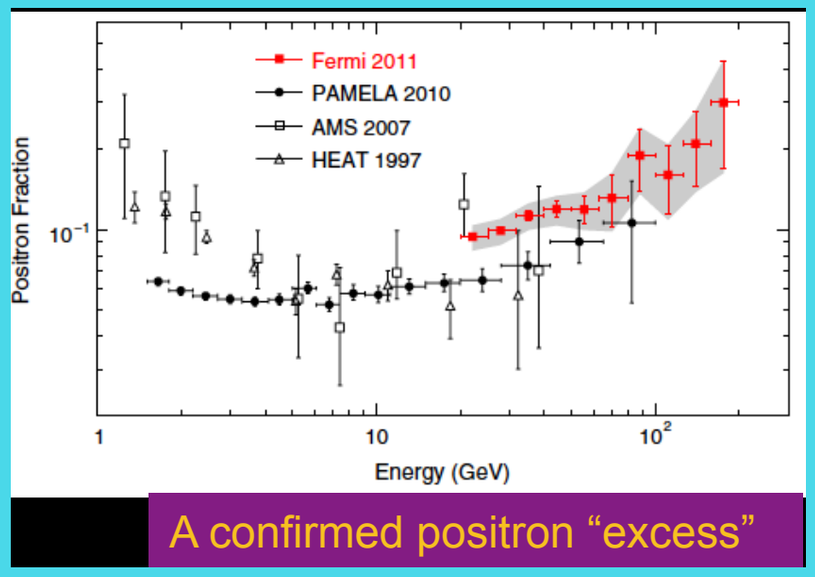

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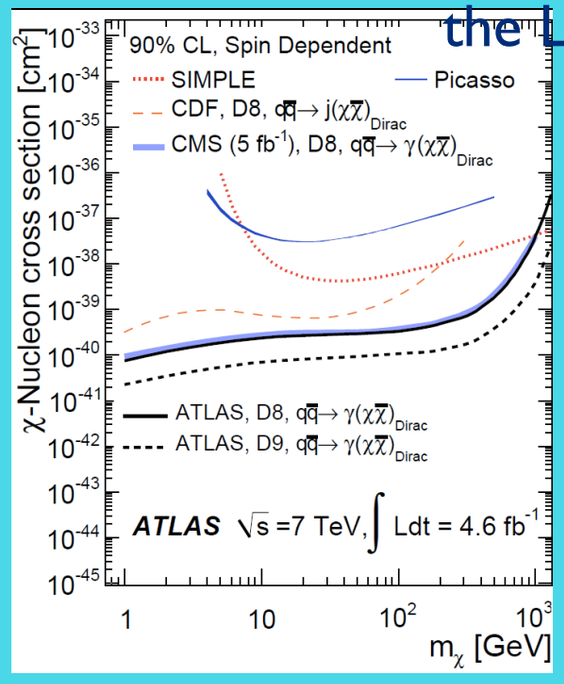
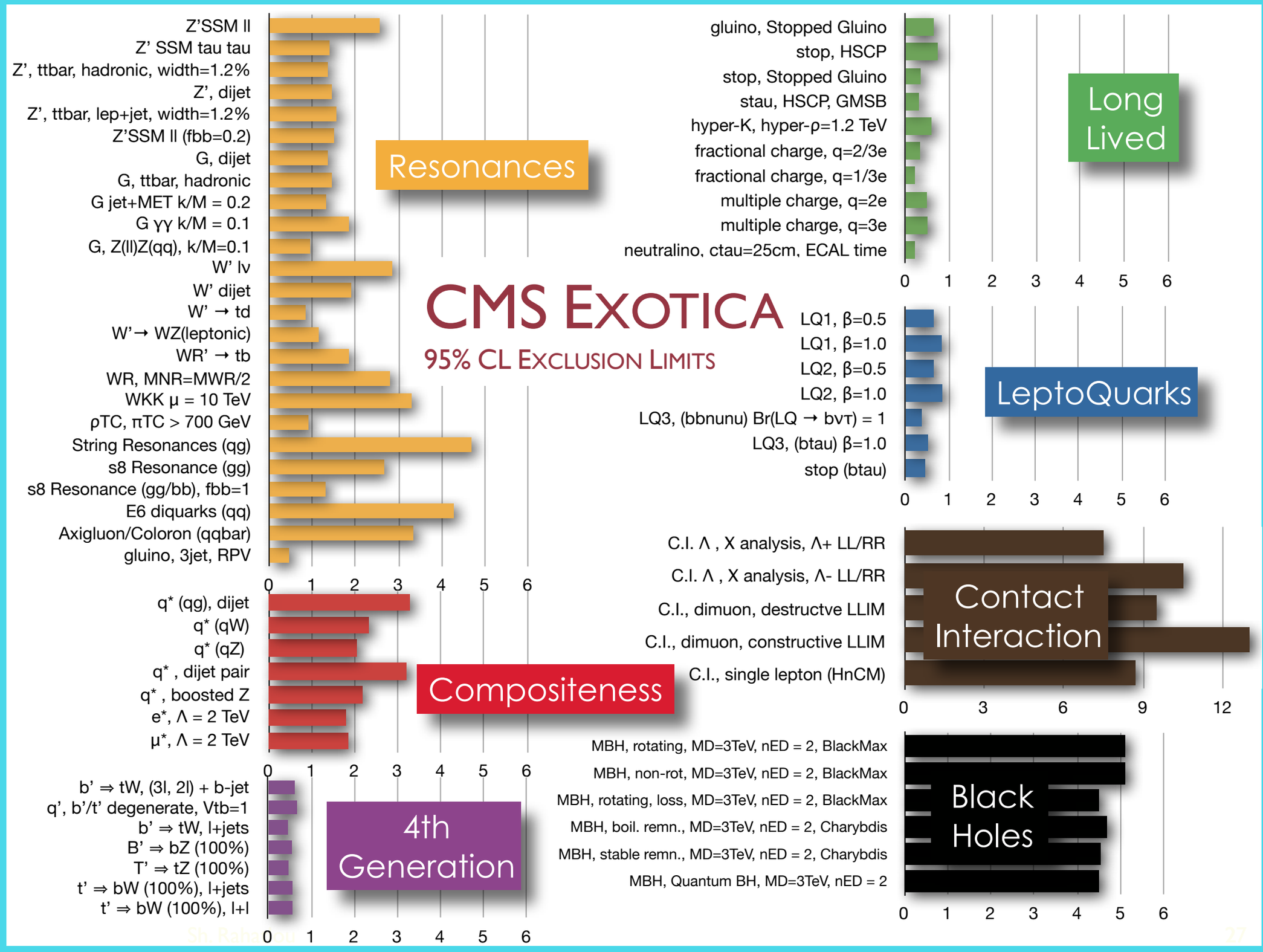


The signal in absent so far!

D.Kazakov Round Table «What Next» Dubna, March 2014

New Particles and Interactions



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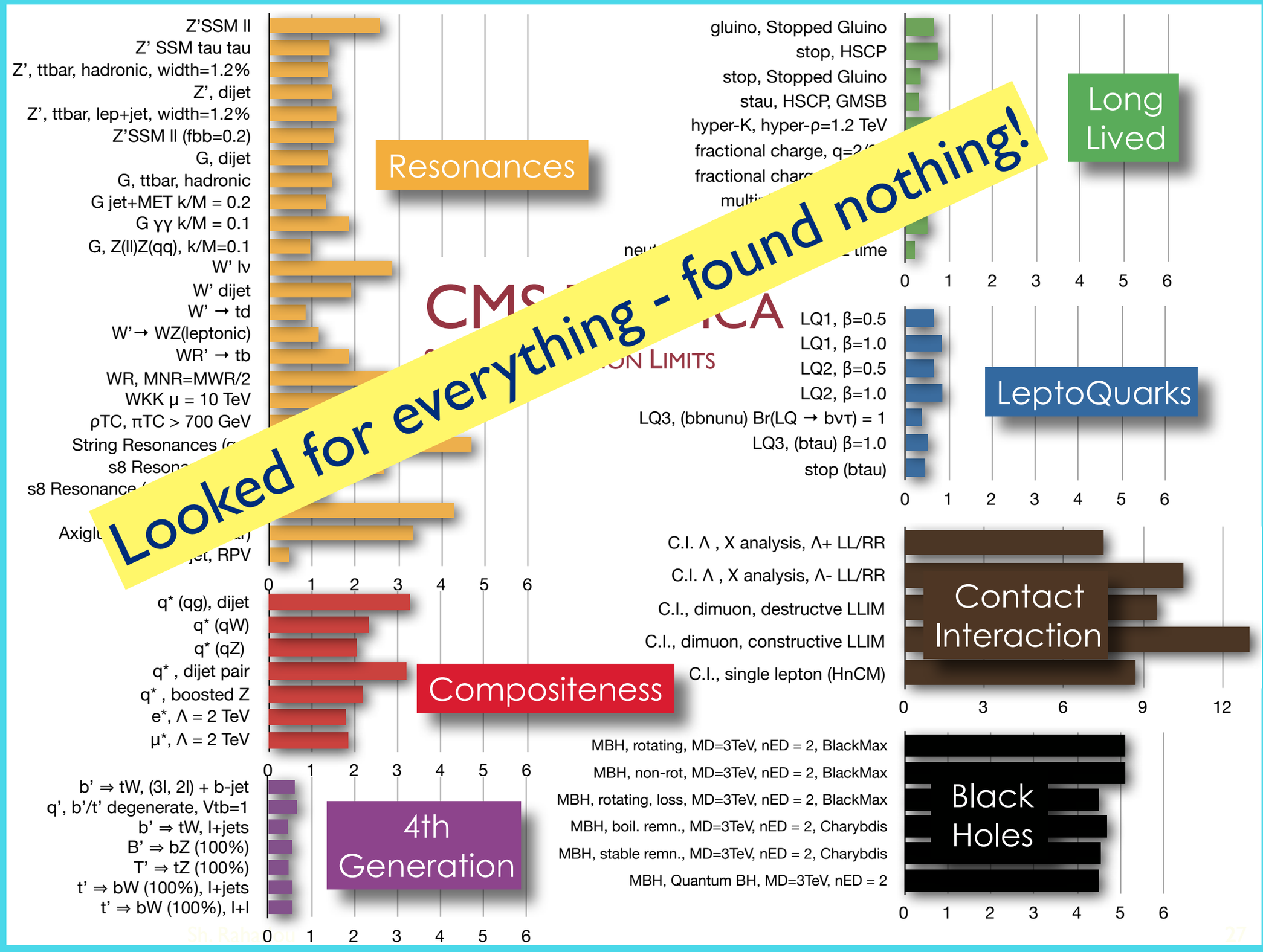

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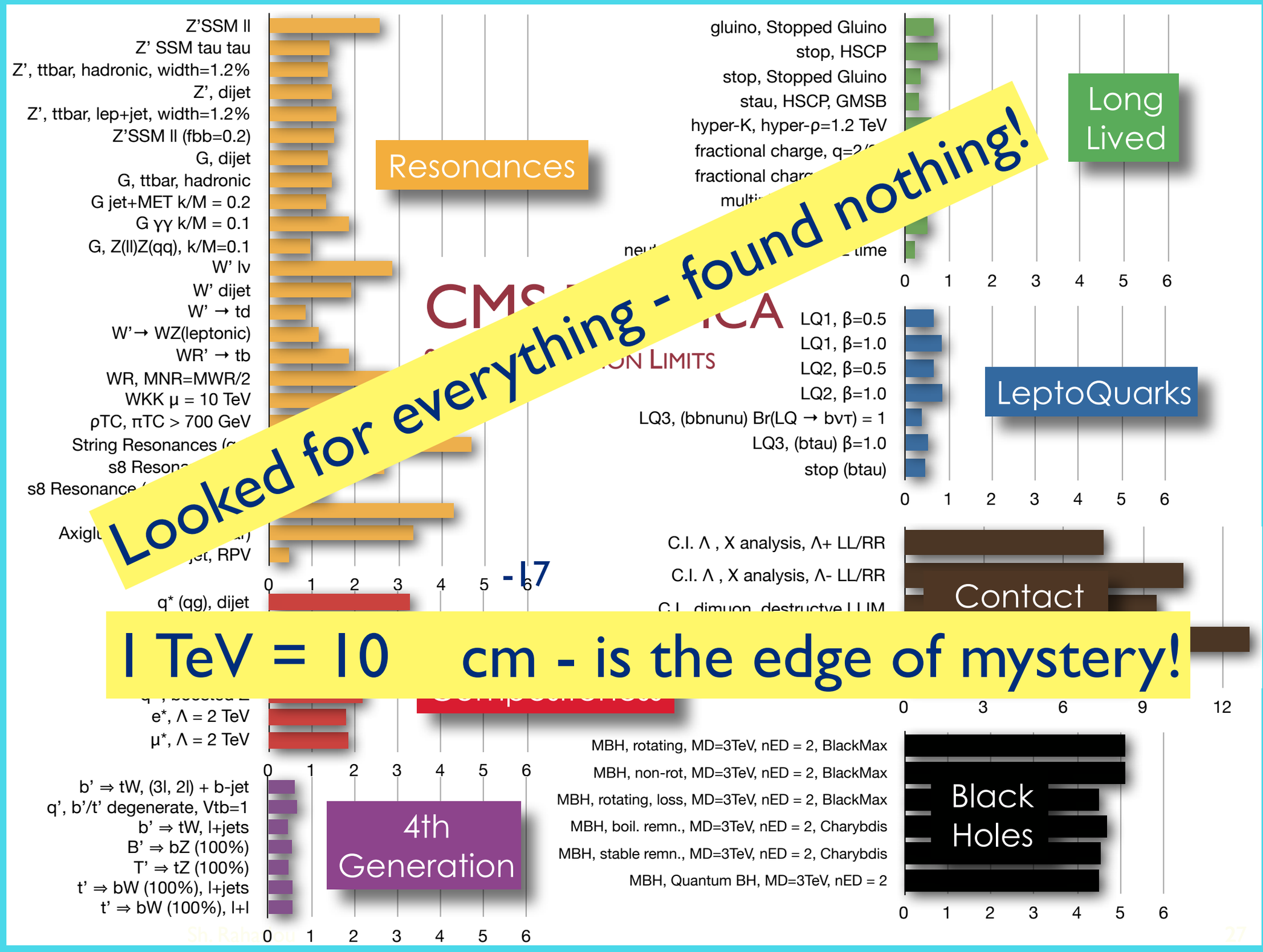

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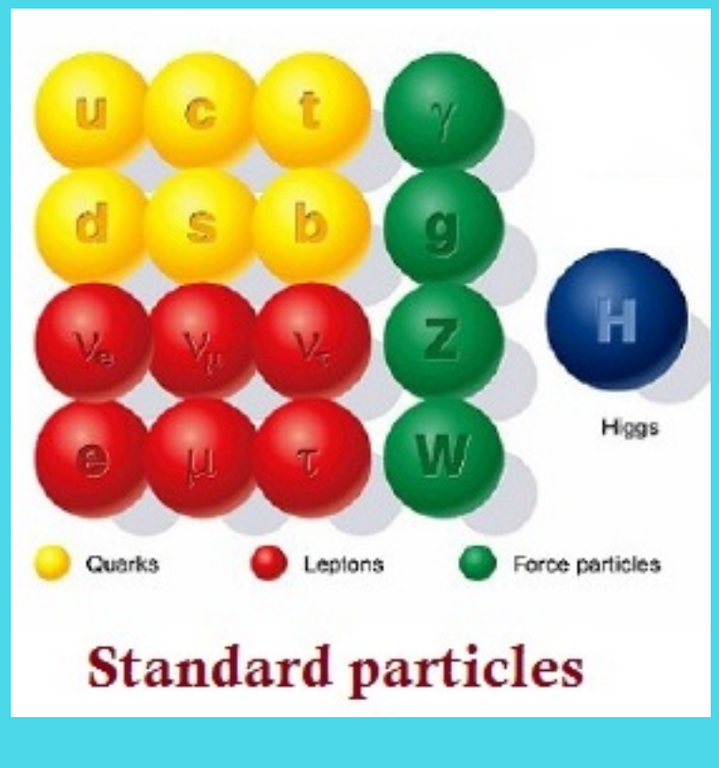

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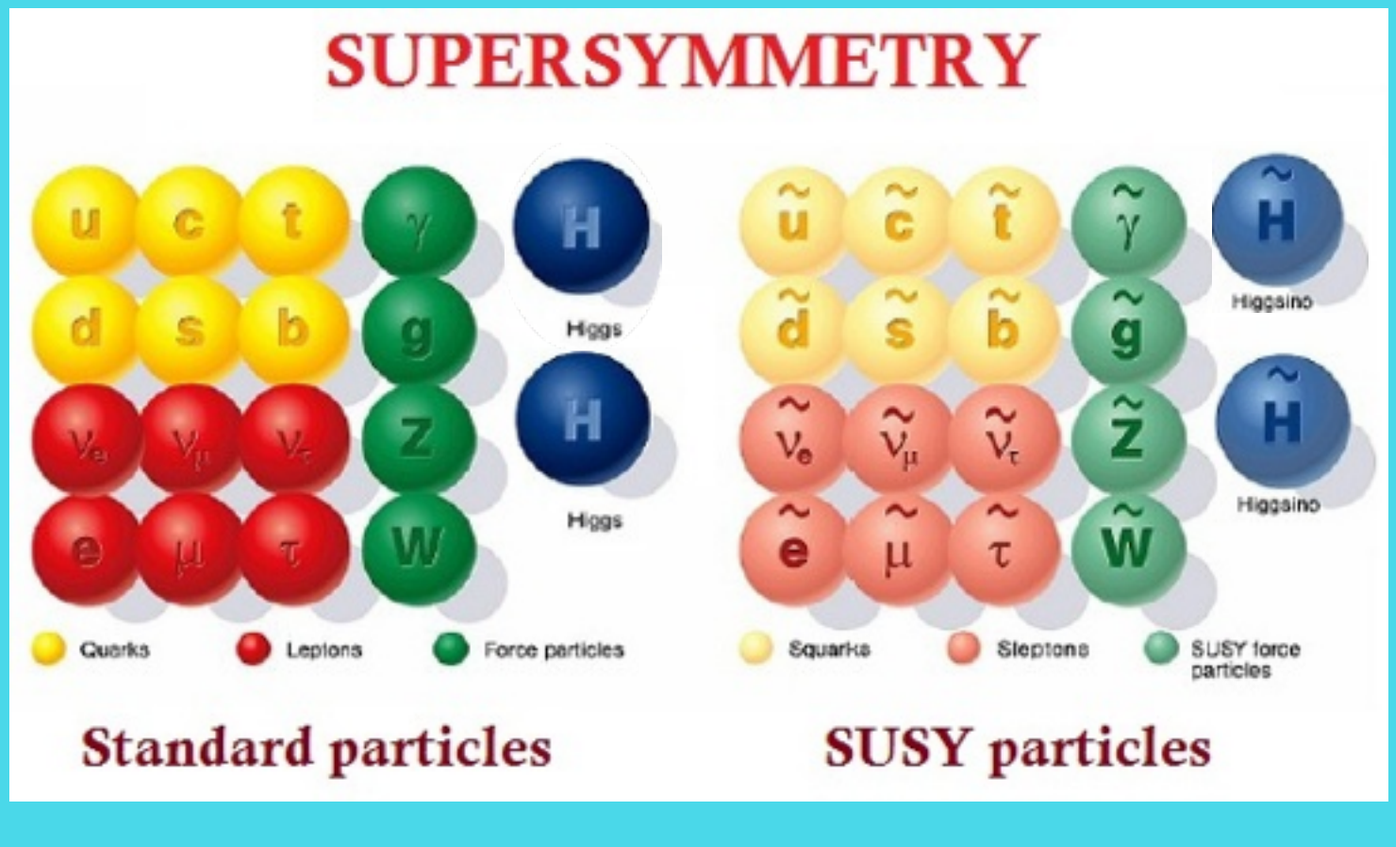

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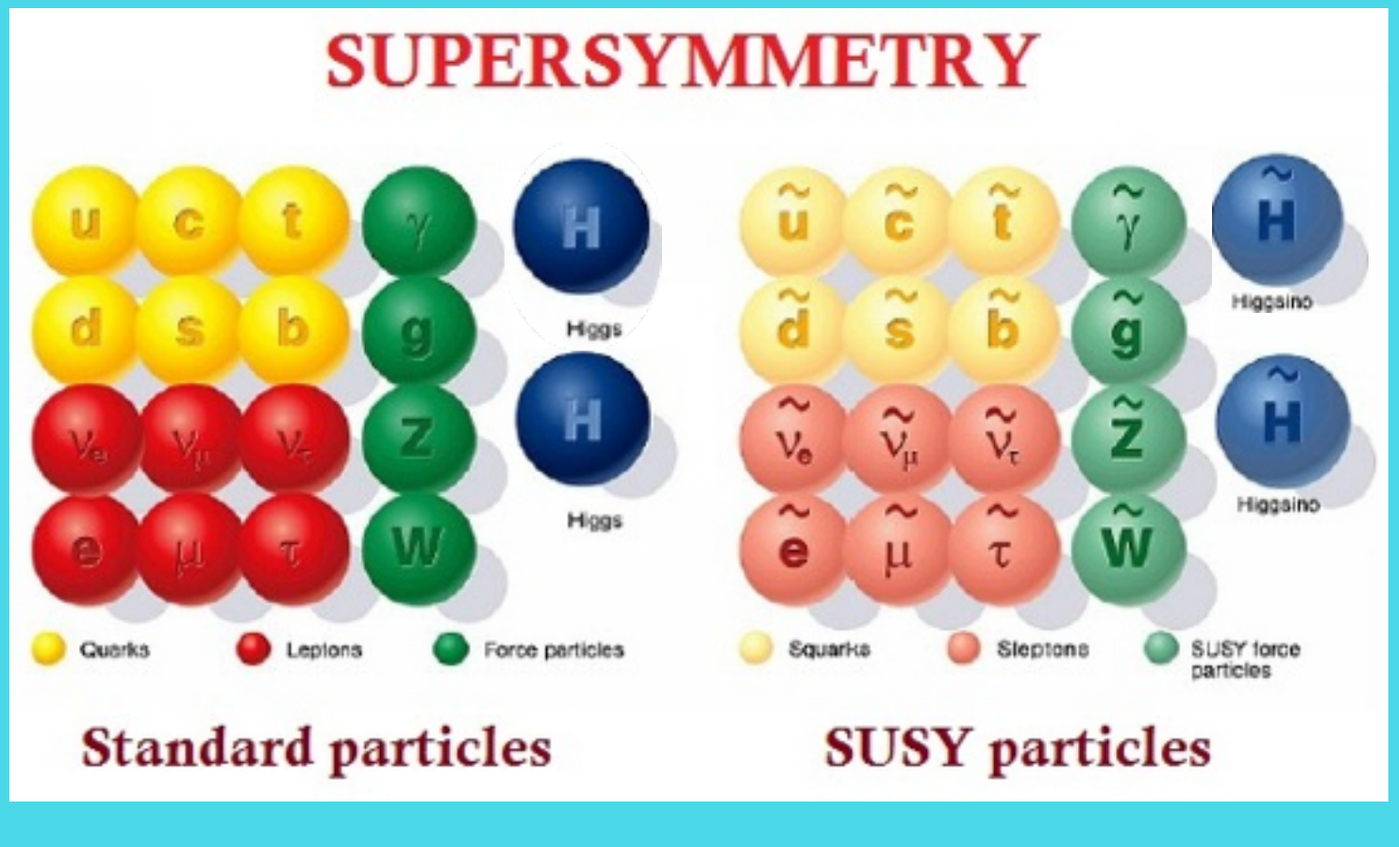
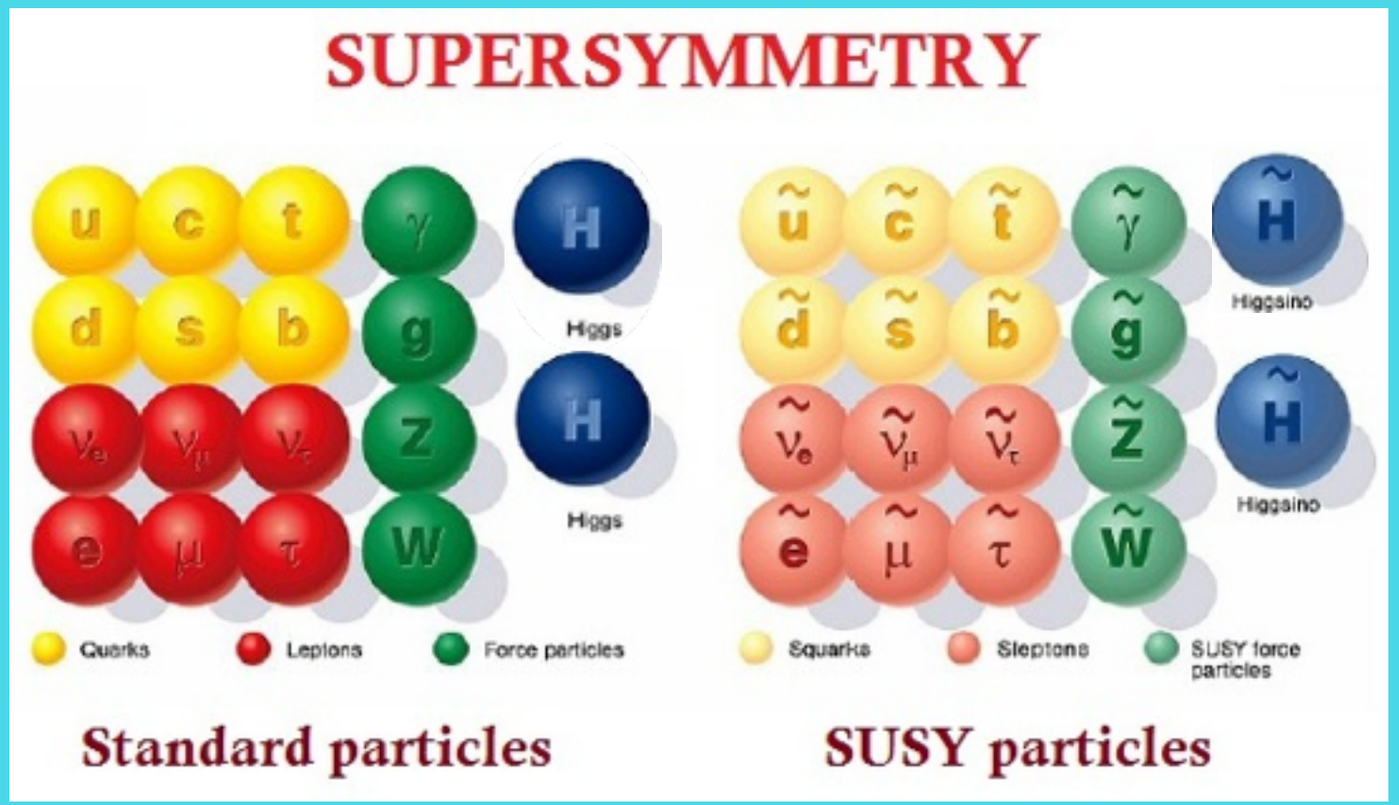


Supersymmetry is a dream of a unified theory of all particles and interactions

New Particles and Interactions



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

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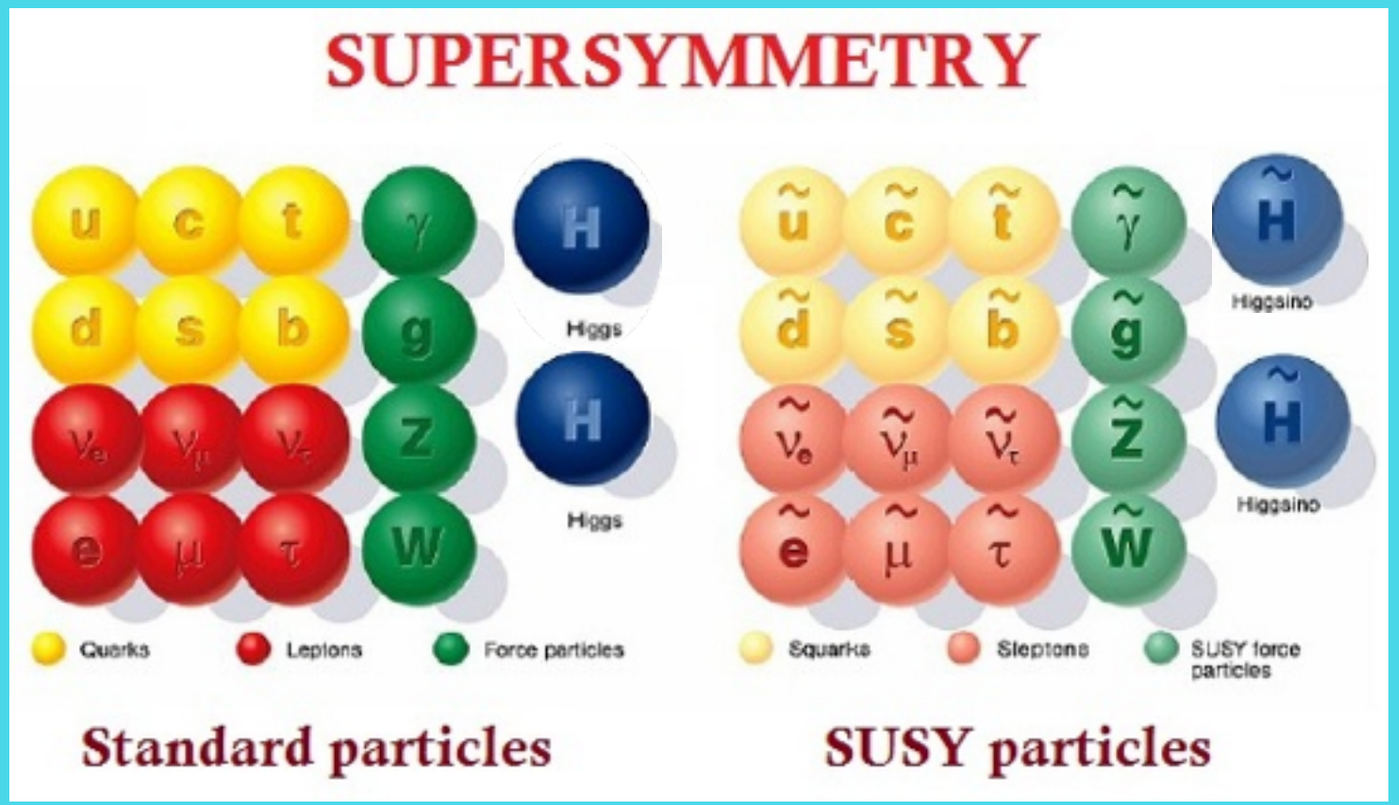
Спин 2 (тензорные поля)	**Гравитационное** $V(r)\sim\frac{A}{r}$		

New Particles and Interactions



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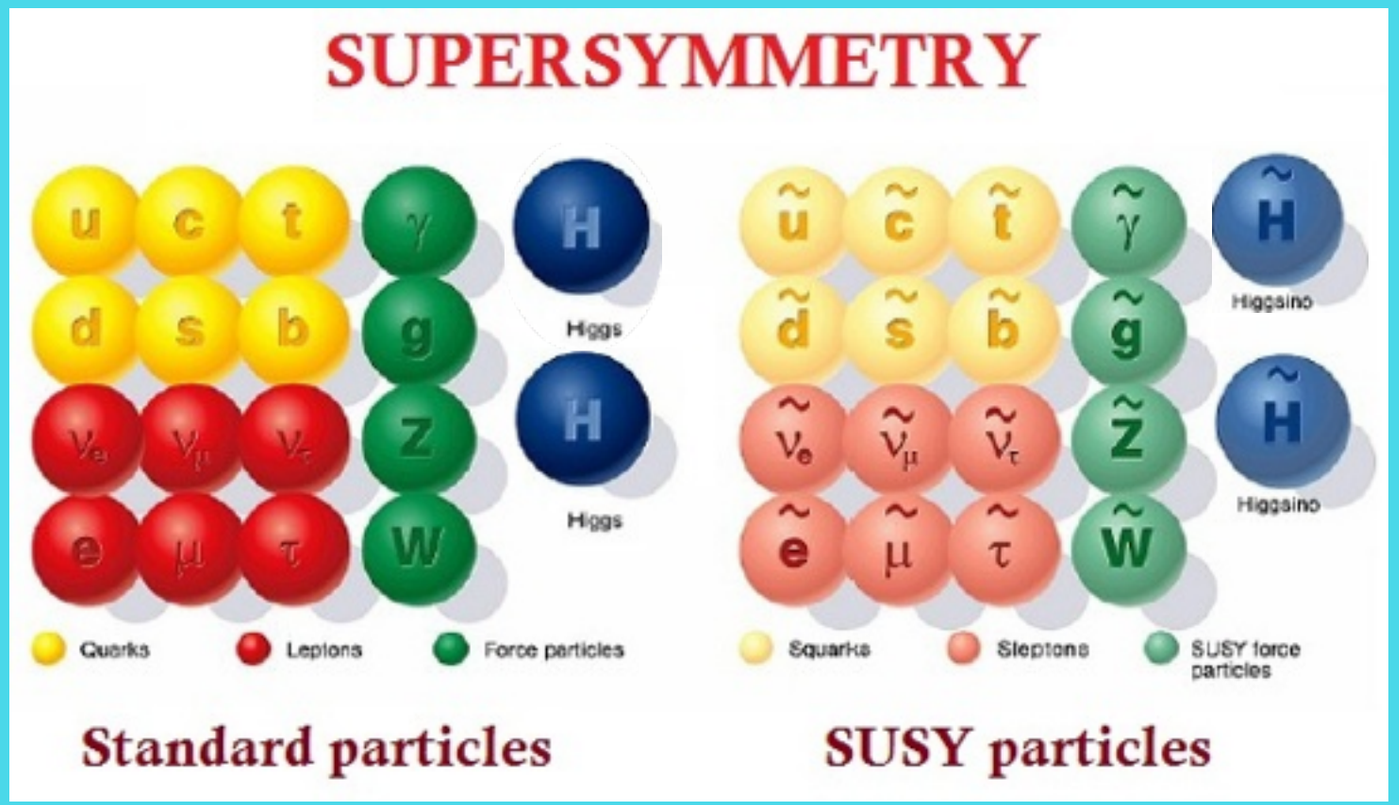
Why SUSY?

New Particles and Interactions



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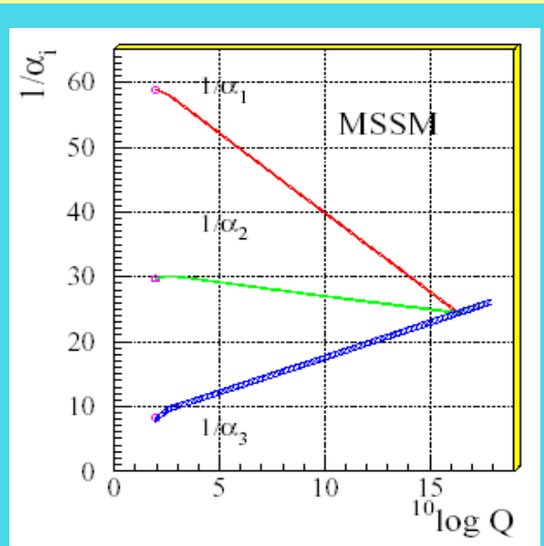
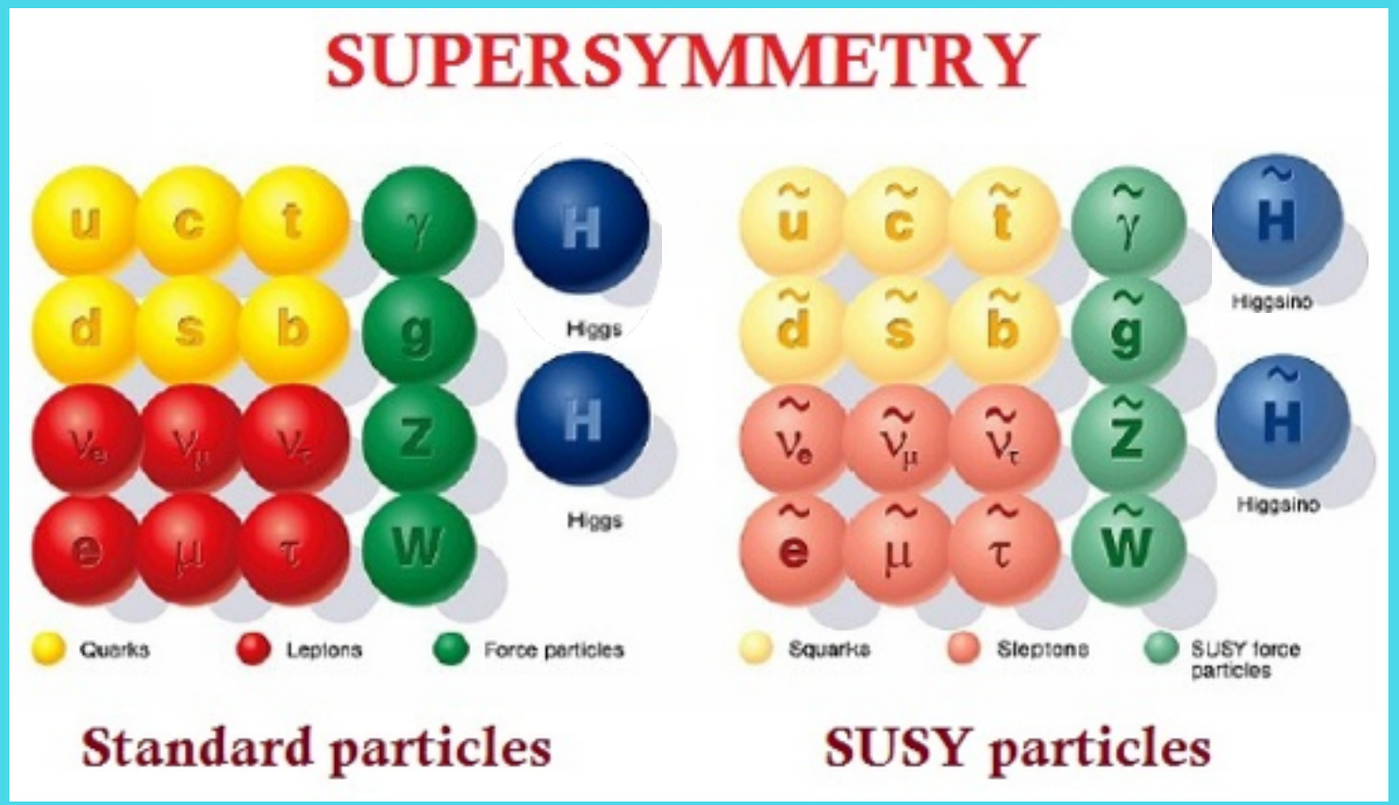
Why SUSY?

- Unification of the gauge couplings



The basis of a grand Unified Theory

New Particles and Interactions



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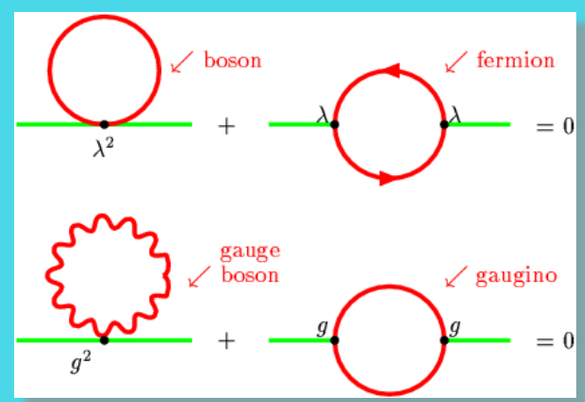
Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem

Cancellations of corrections and stabilization of the Higgs potential



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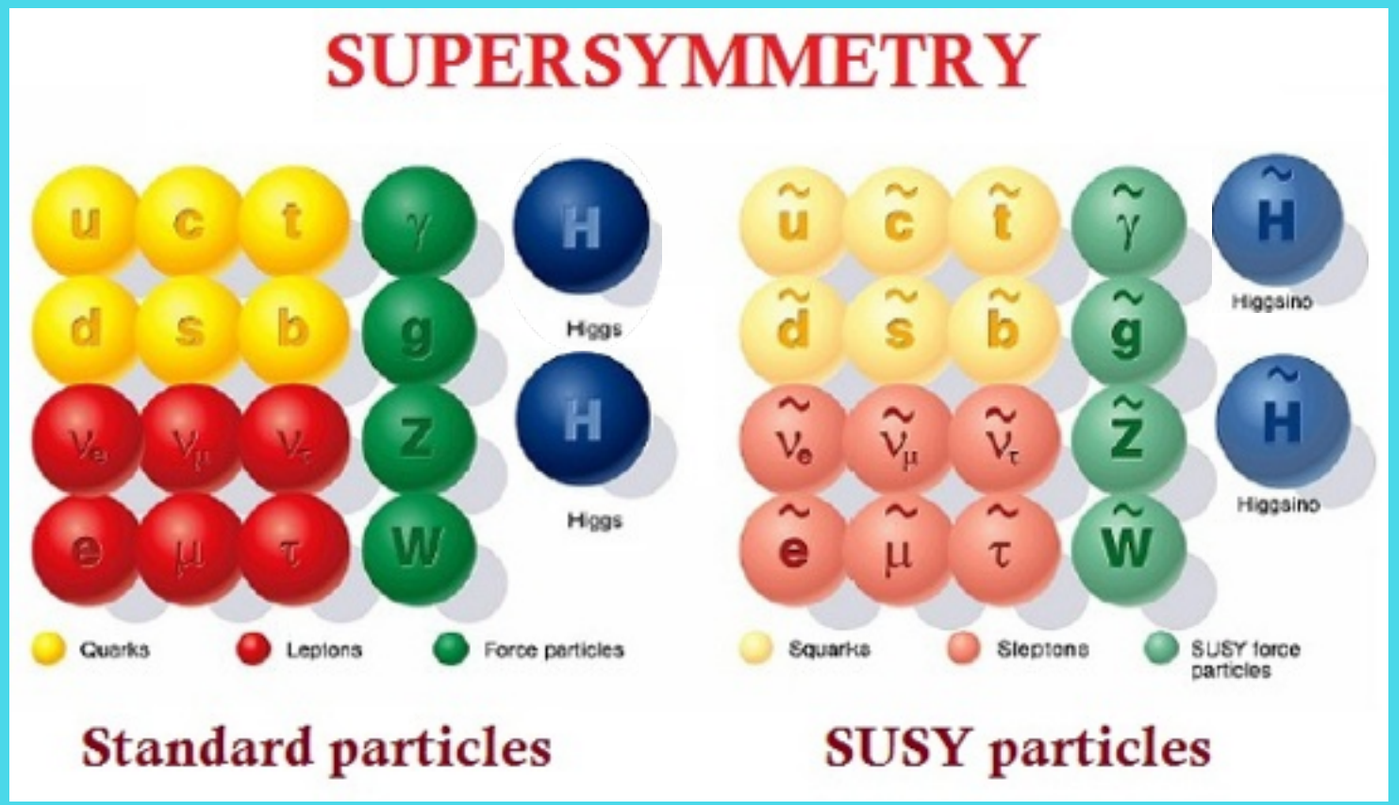

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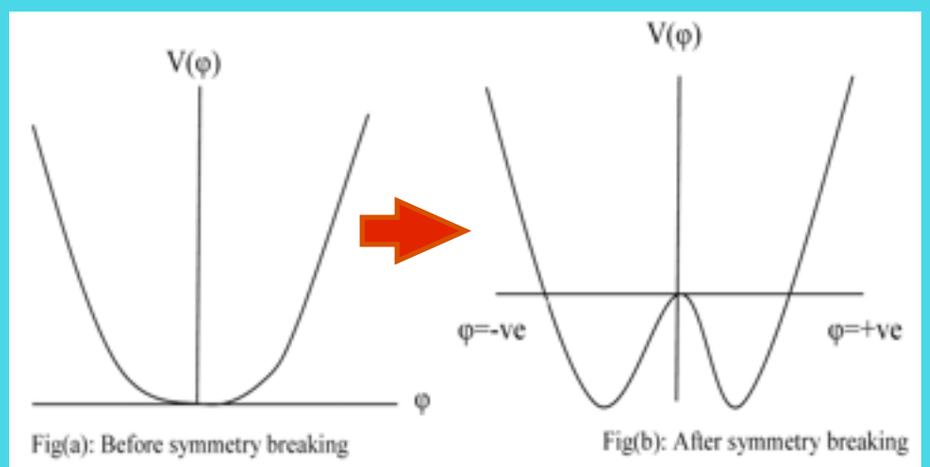
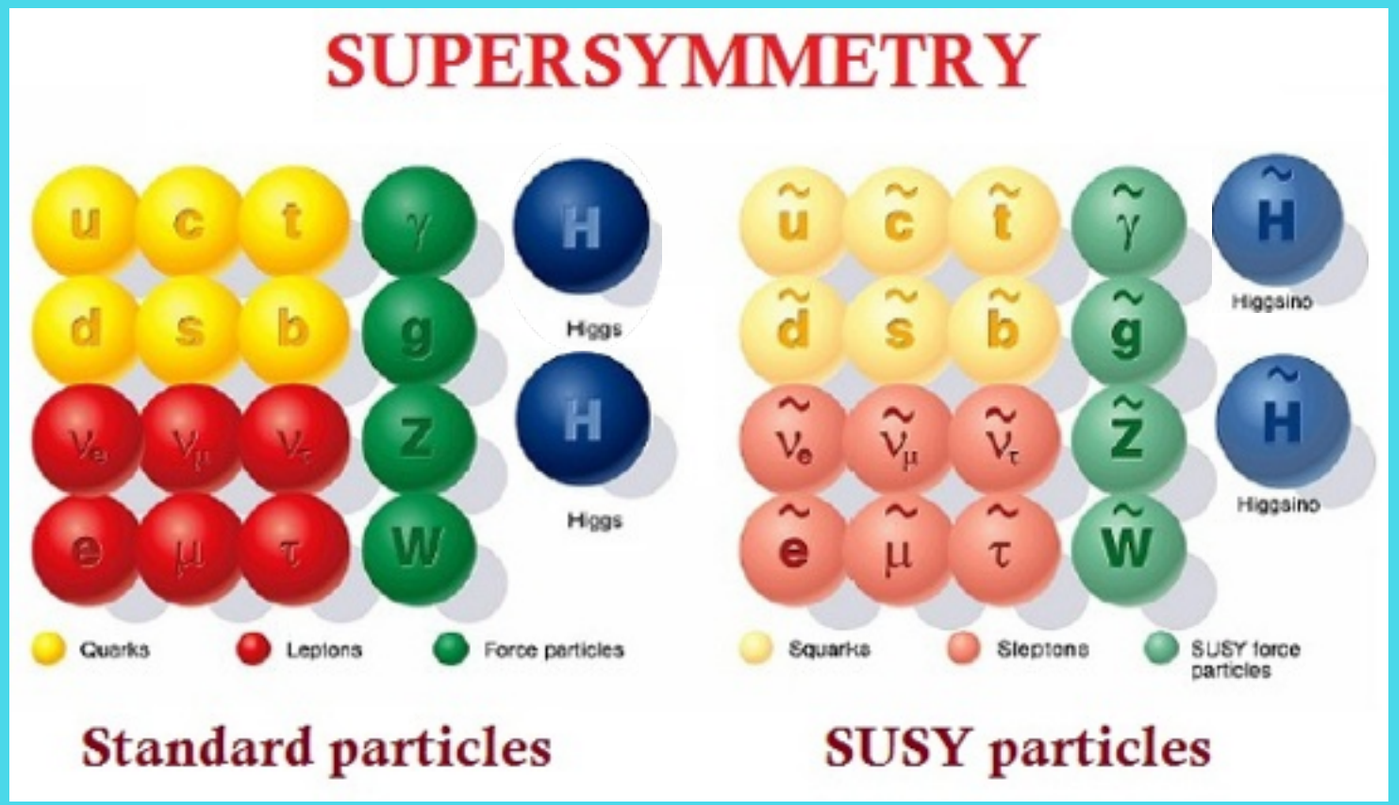
- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation



Violation of symmetry comes from radiative corrections

New Particles and Interactions



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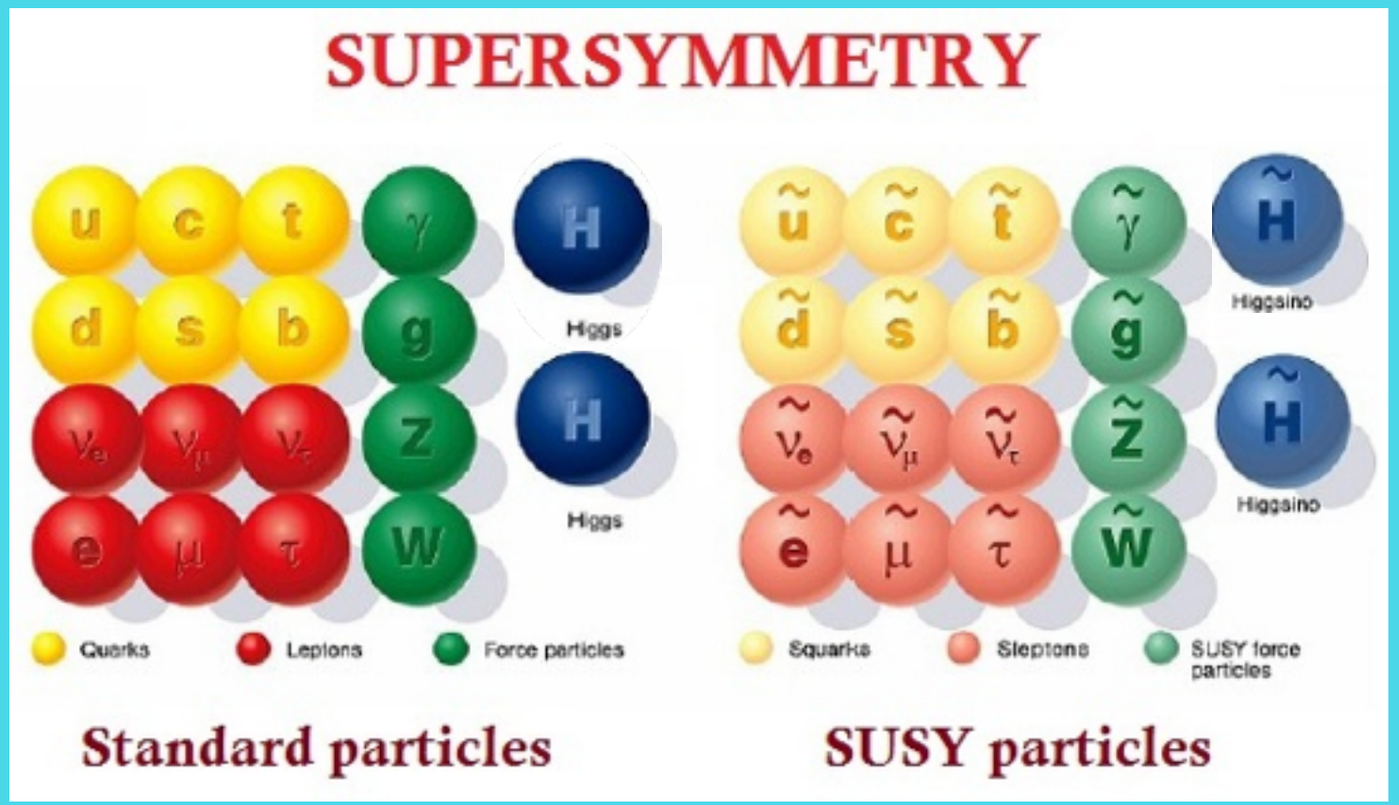
Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

Neutralino

New Particles and Interactions



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Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle
- Unification with gravity!

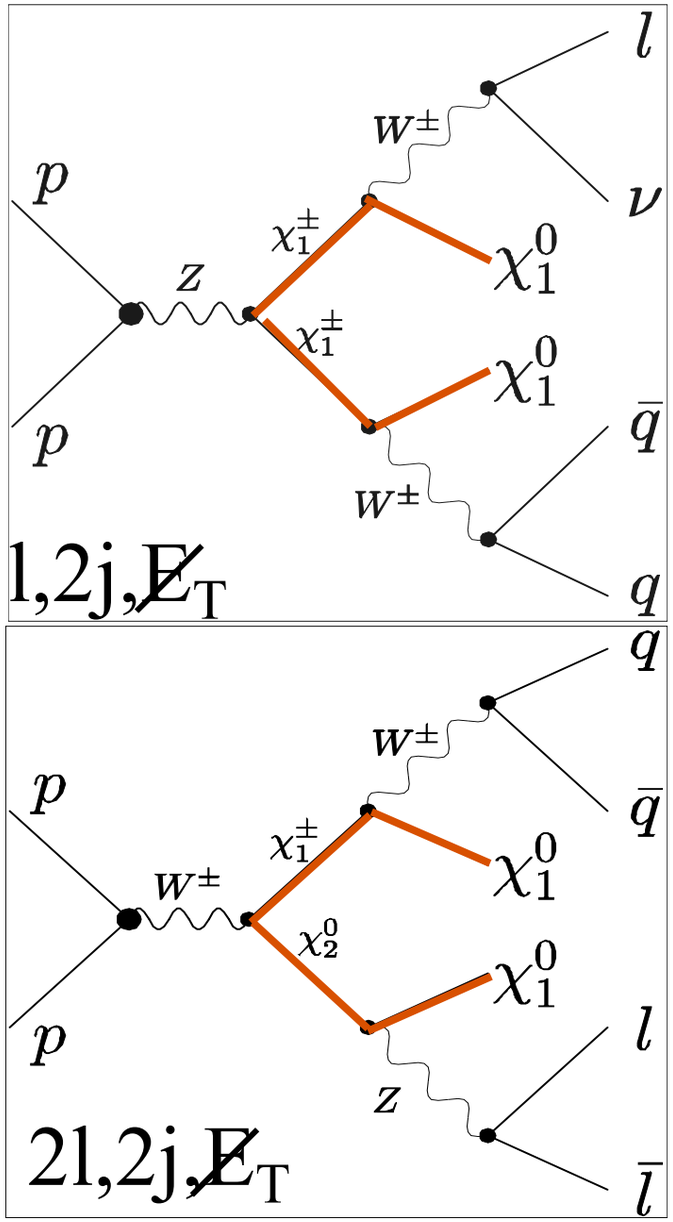
$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \overline{\delta}_{\bar\varepsilon}\} = 2(\varepsilon\sigma^\mu\bar\varepsilon)P_\mu$$

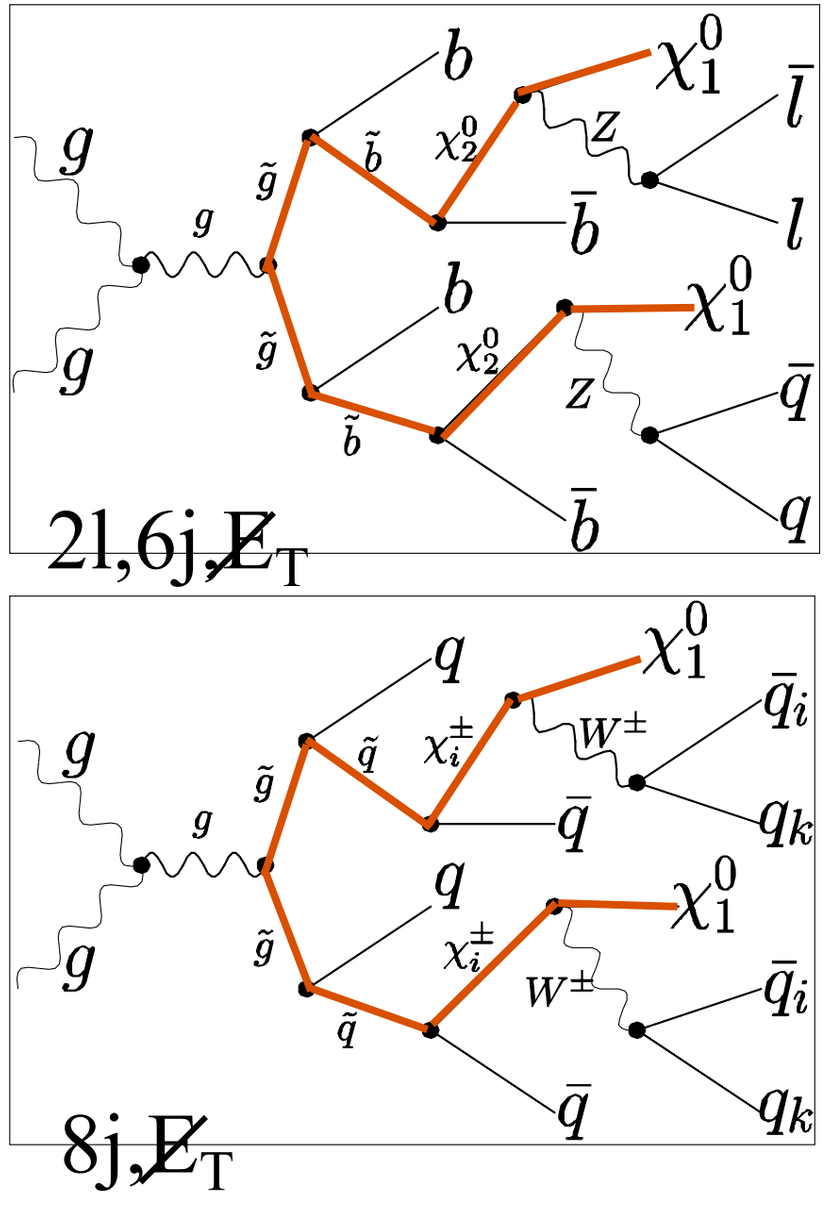
$$\varepsilon = \varepsilon(x) \text{ local coordinate transf. } \Rightarrow \text{ (super)gravity}$$

Local supersymmetry = general relativity !

Creation and decay of superpartners @ LHC

Weak int's



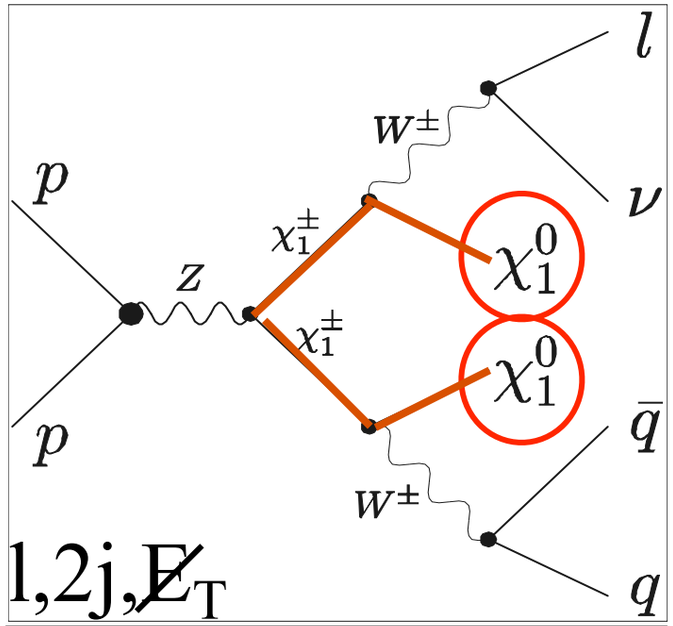


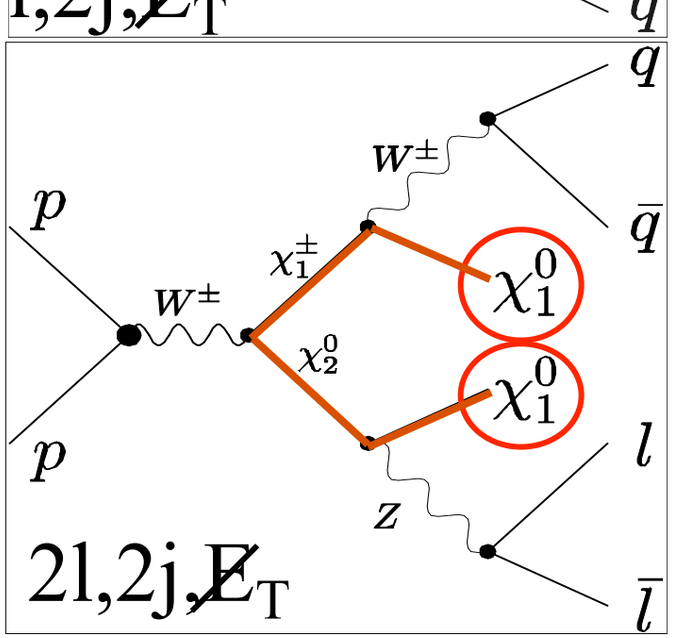
Strong int's

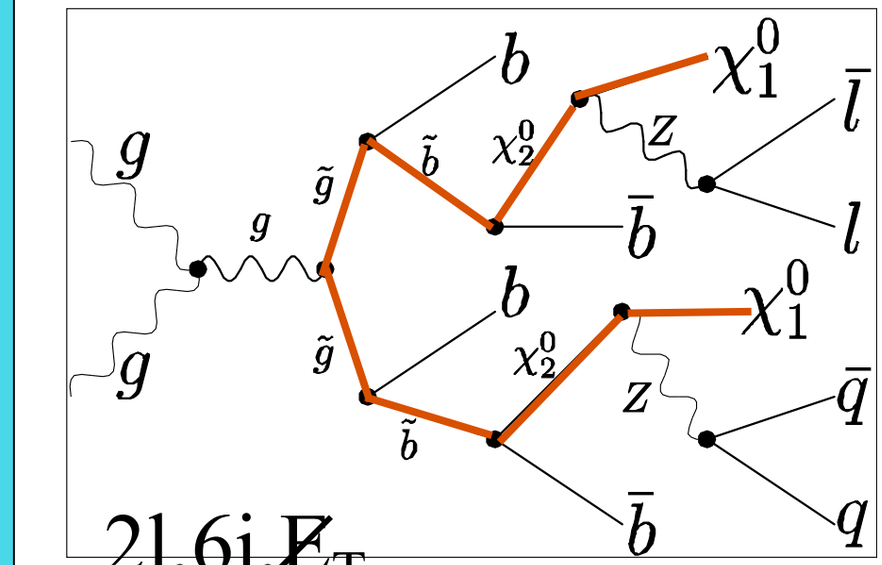
Typical SUSY signature: missing energy and transverse momentum

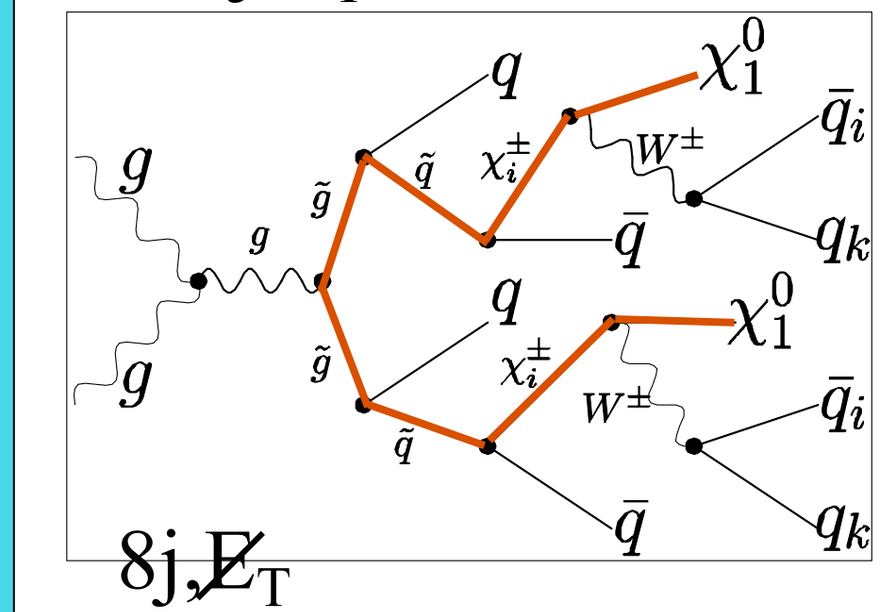
Creation and decay of superpartners @ LHC

Weak int's









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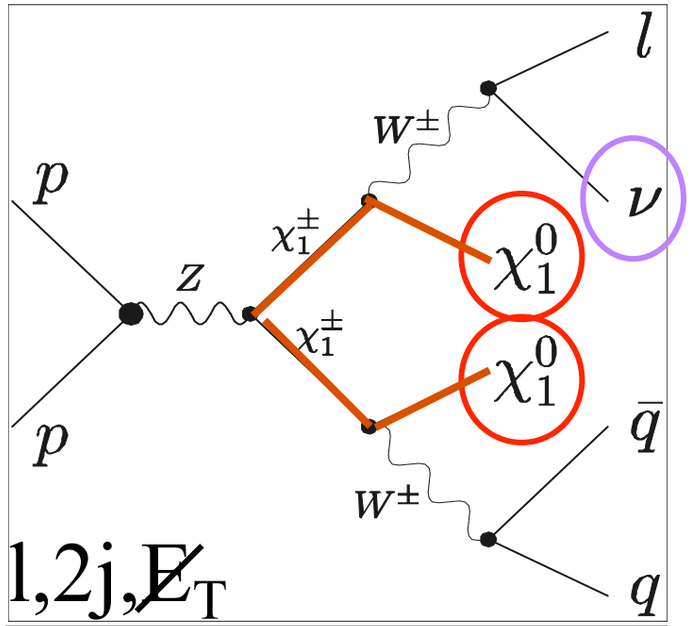

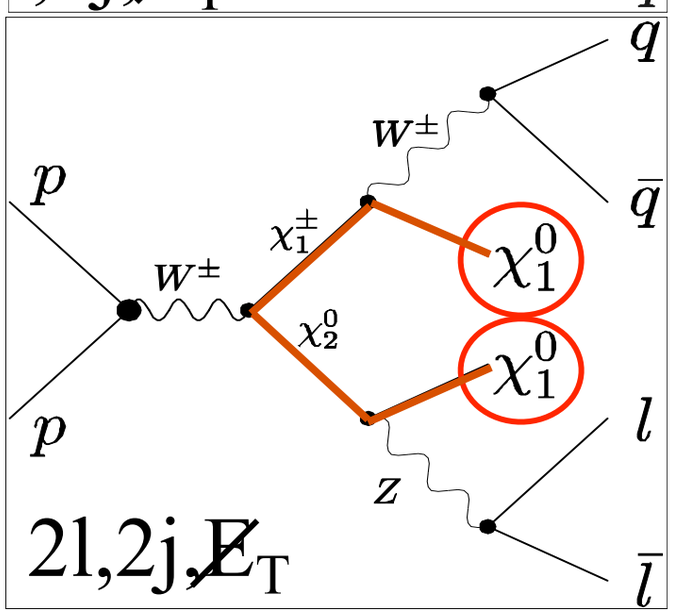

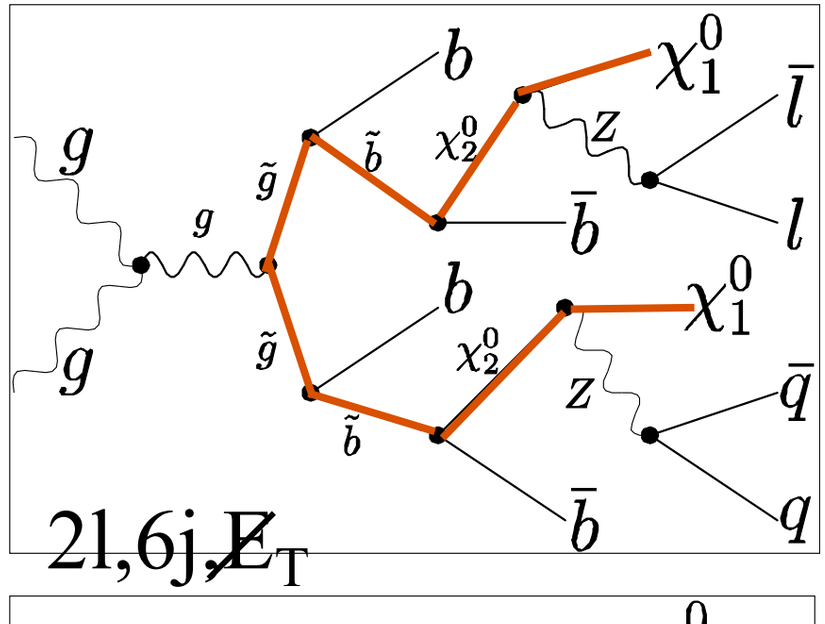

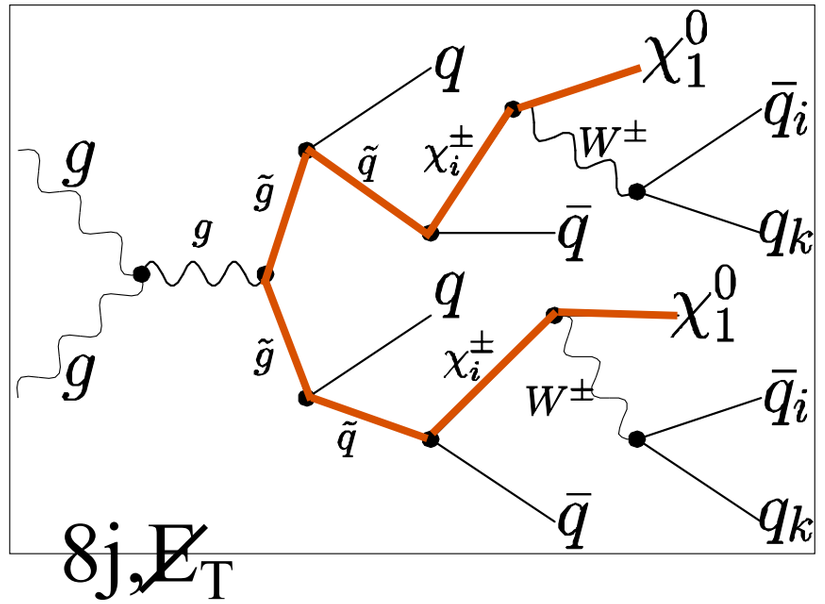

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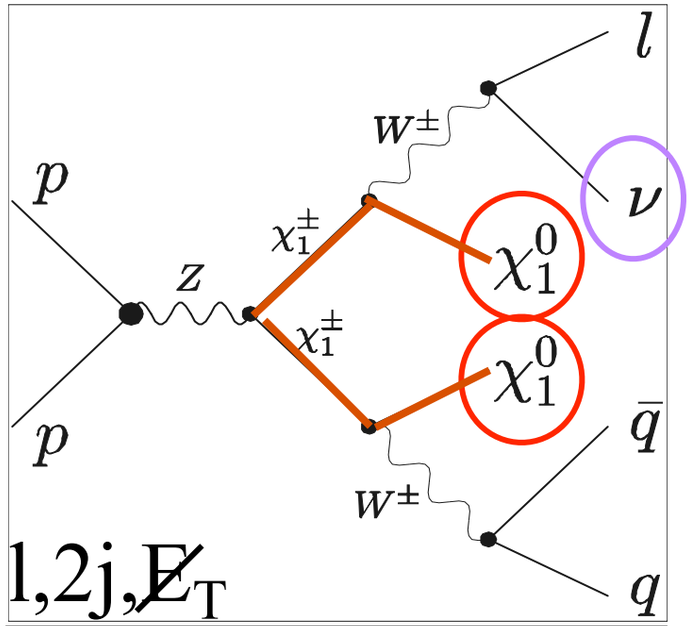
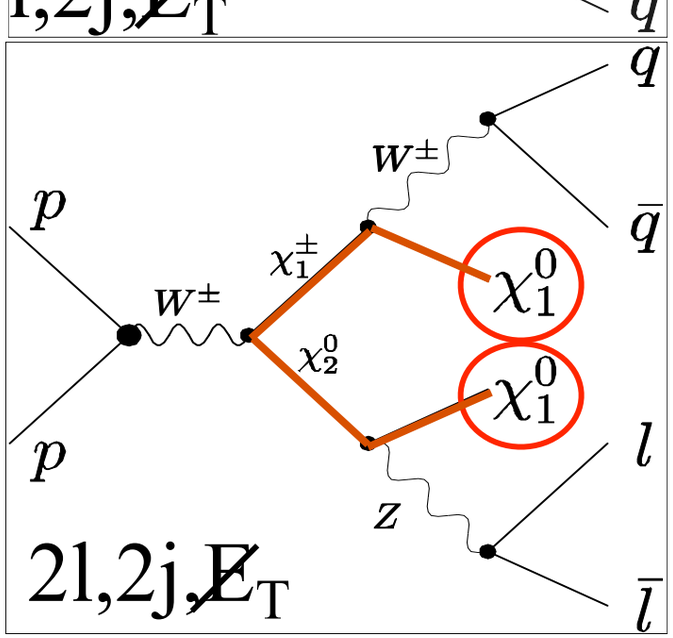
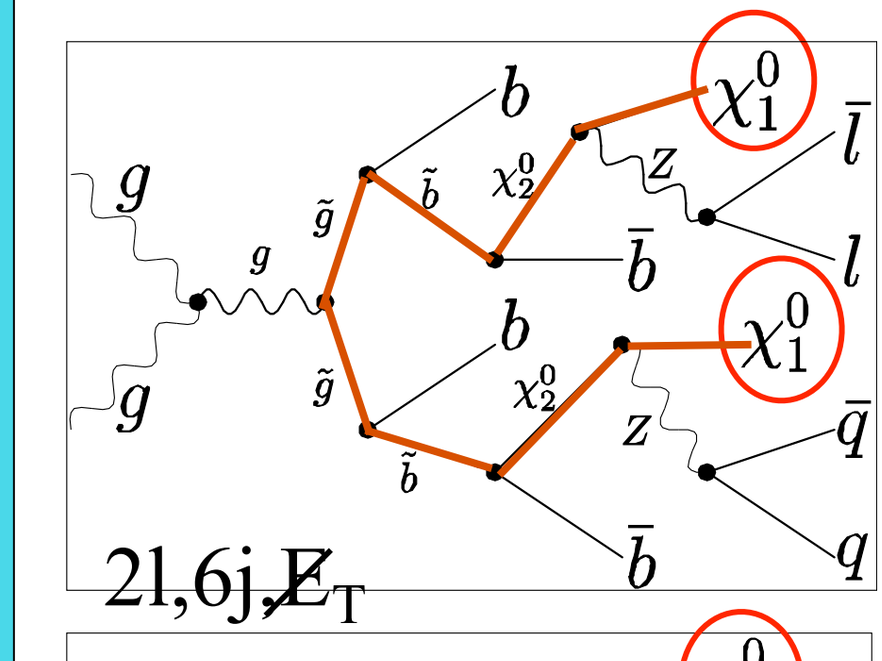
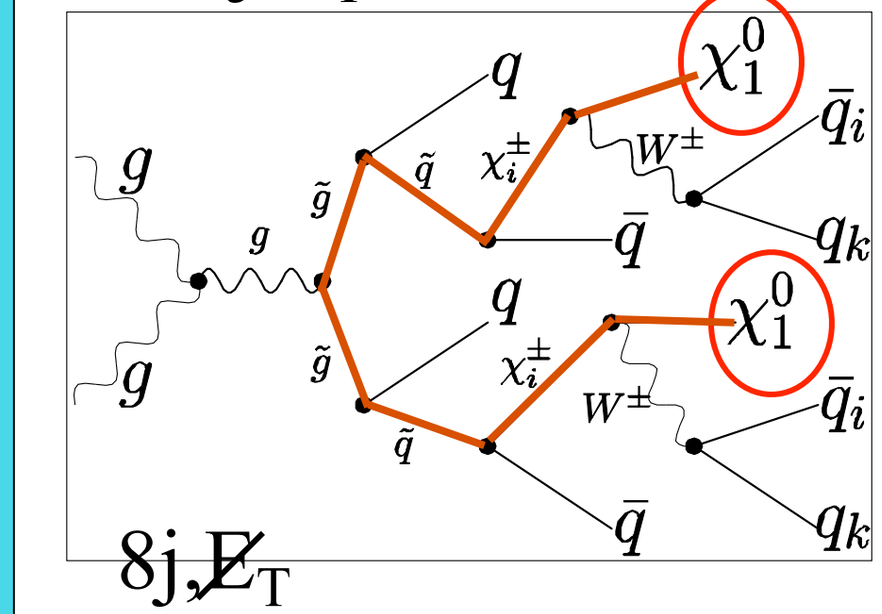




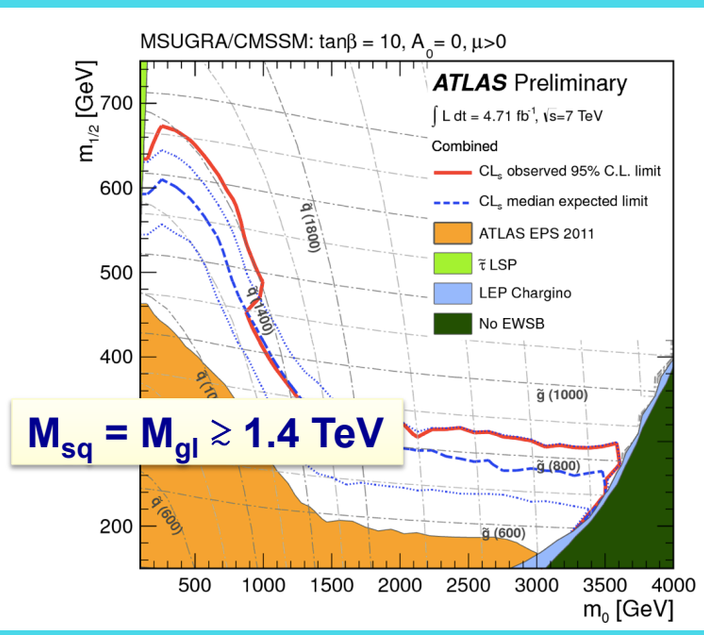




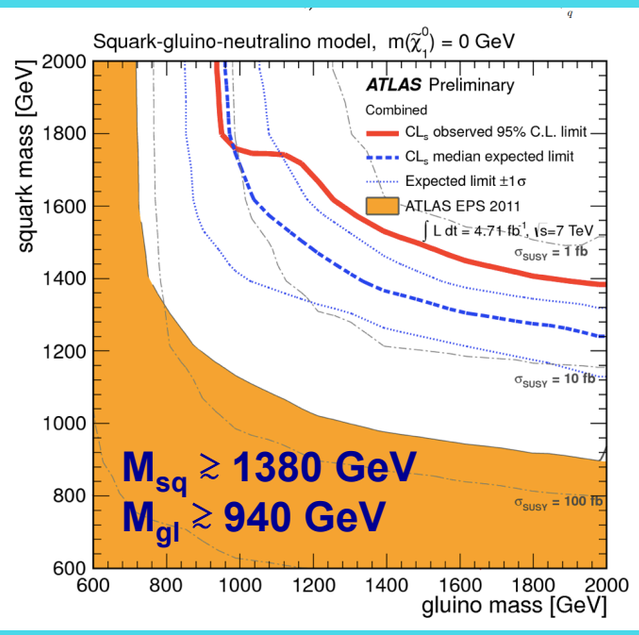
Strong int's

Typical SUSY signature: missing energy and transverse momentum

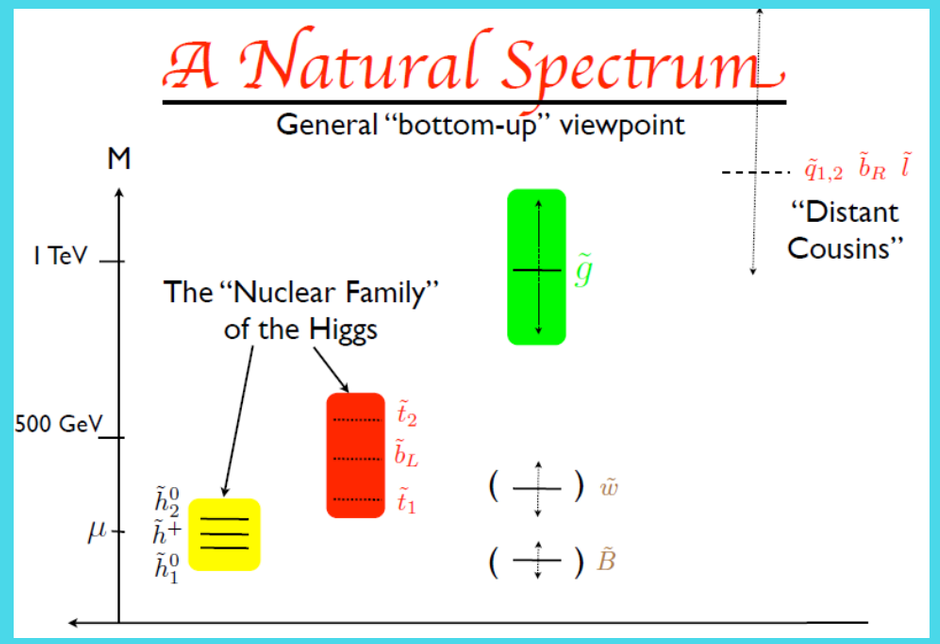
Search for Supersymmetry @ LHC



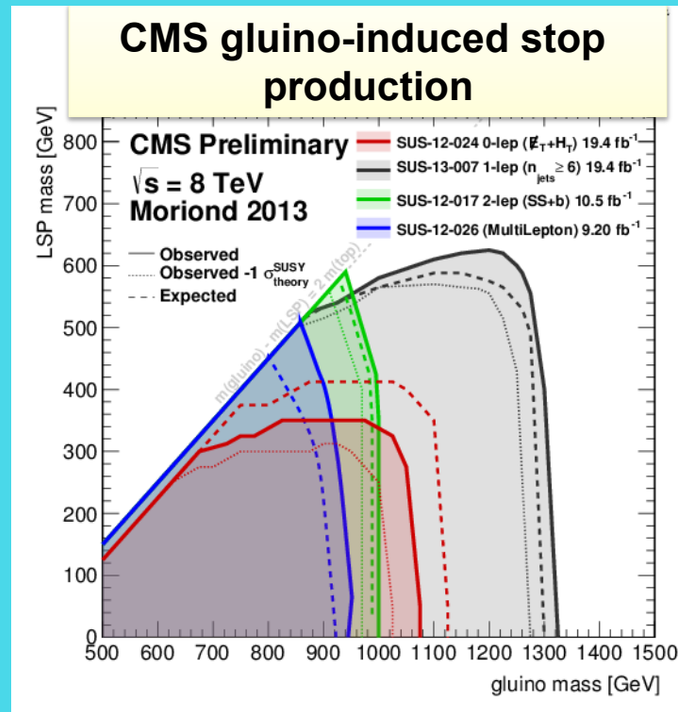
$M_{sq} = M_{gl} \gtrsim 1.4$ TeV

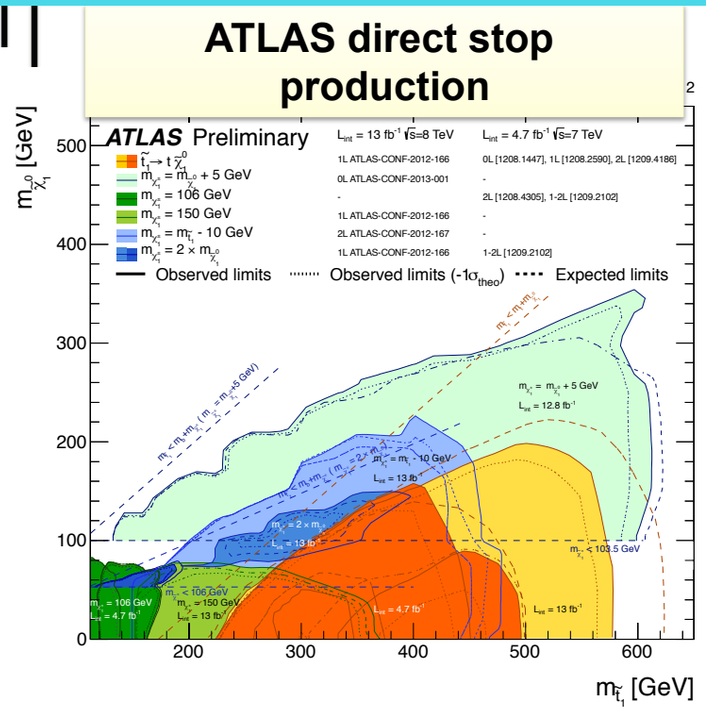


$M_{sq} \gtrsim 1380$ GeV
$M_{gl} \gtrsim 940$ GeV



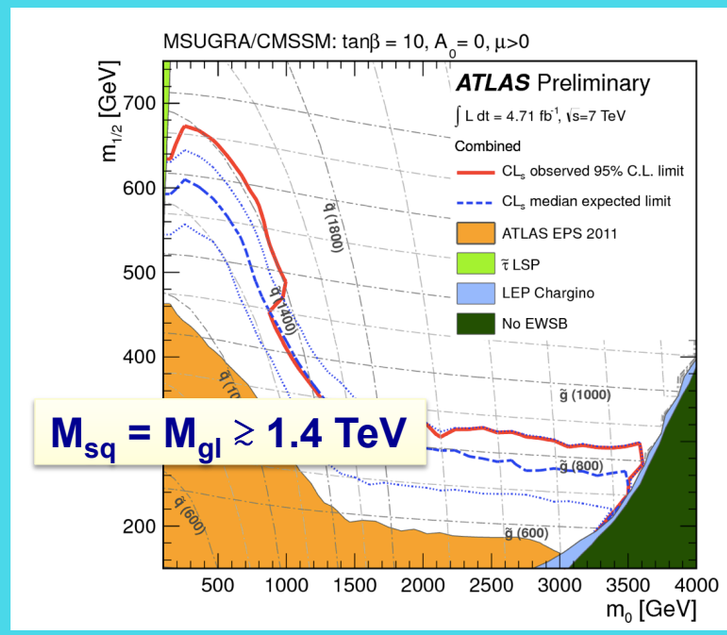
Weakly interacting particles





Strongly interacting particles

Search for Supersymmetry @ LHC



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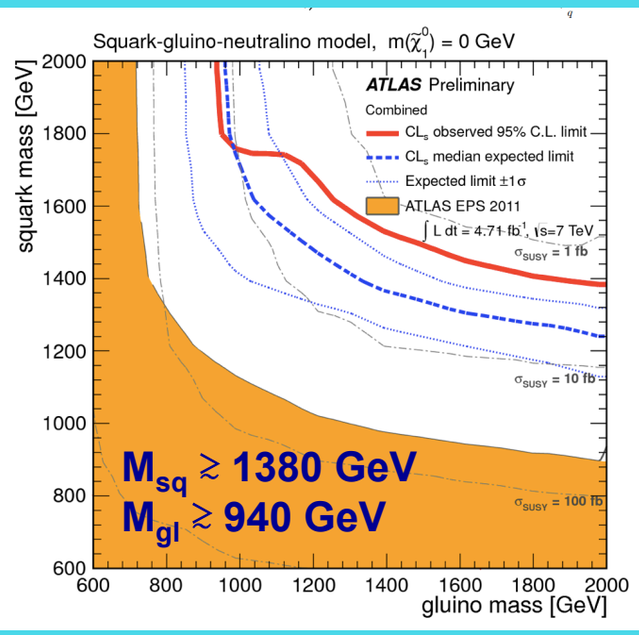

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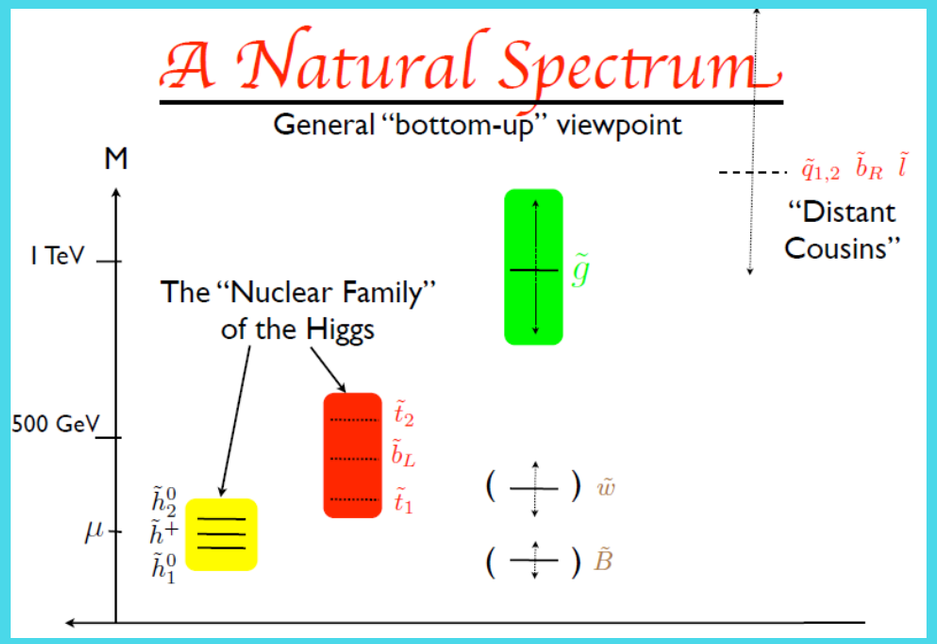
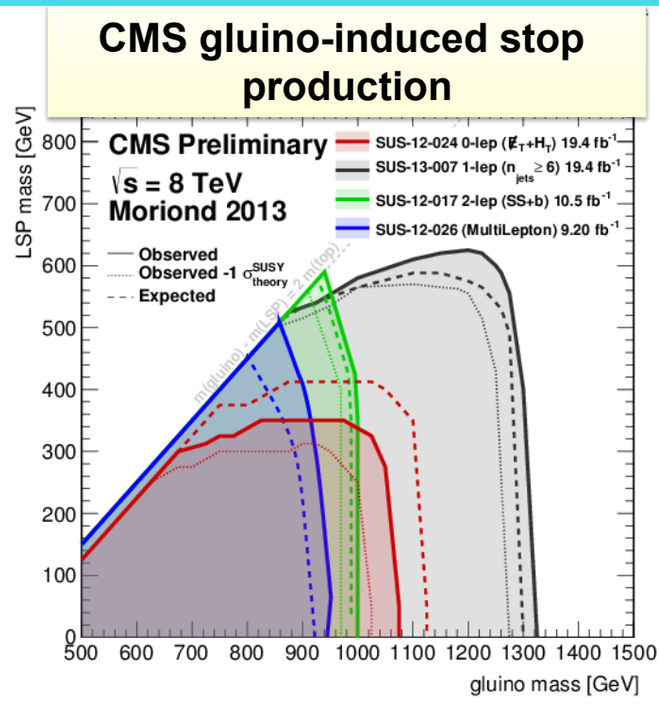
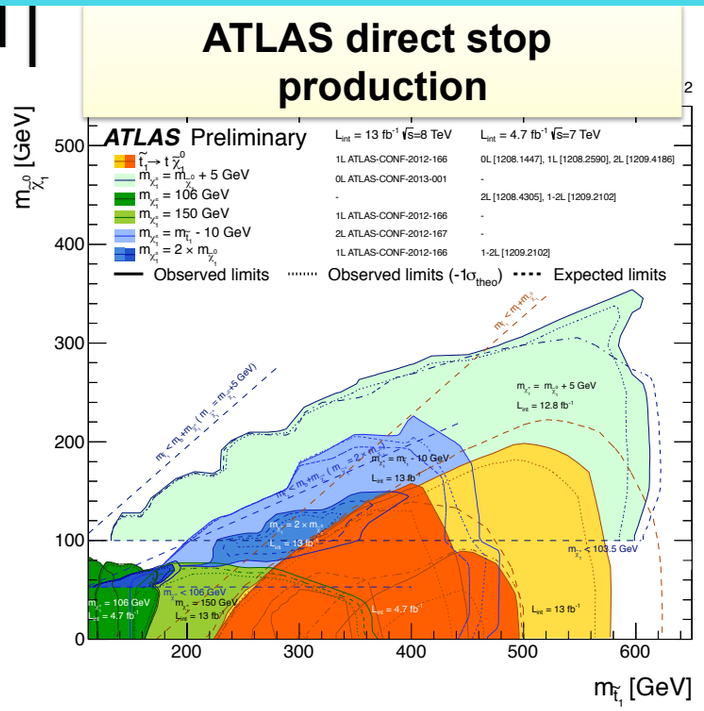


Weakly interacting particles

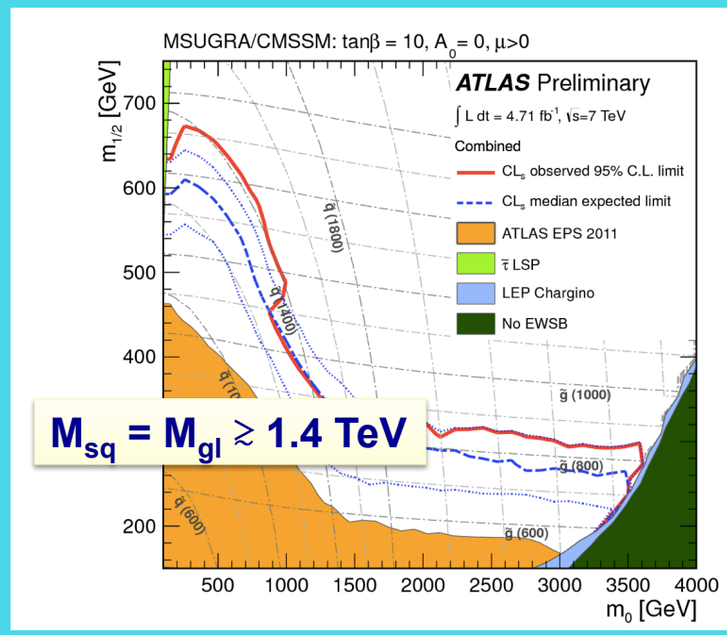




Strongly interacting particles

Tremendous progress of the LHC on SUSY searches is dissapointing so far.

Search for Supersymmetry @ LHC



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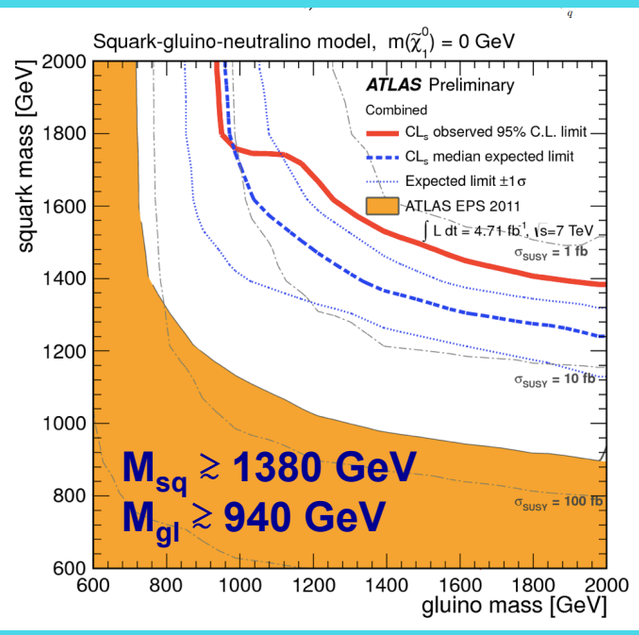

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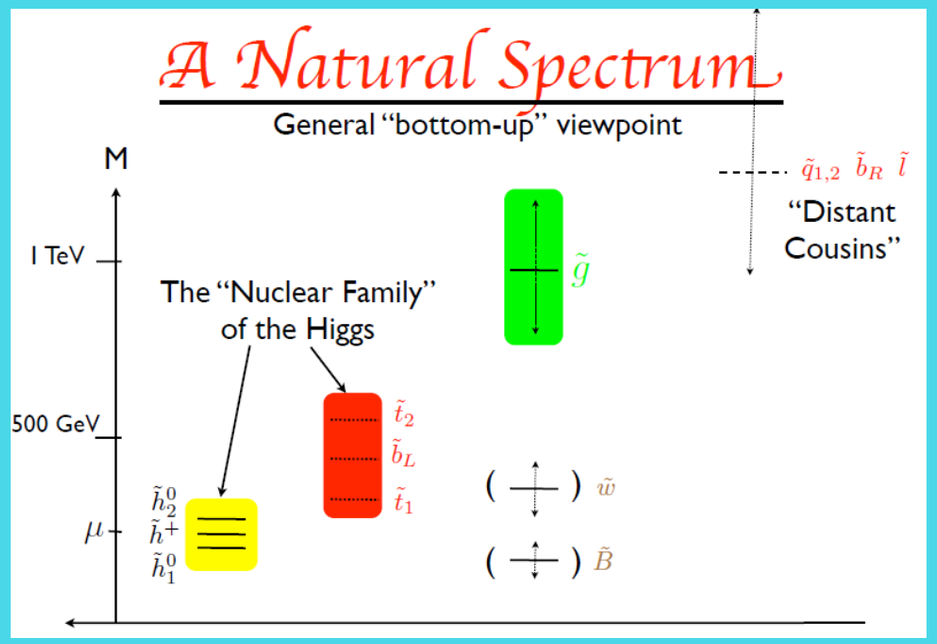
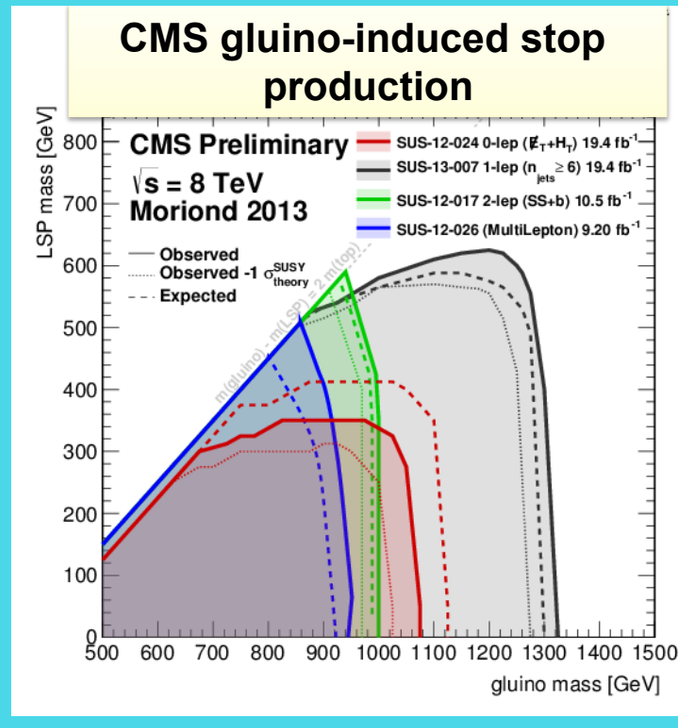
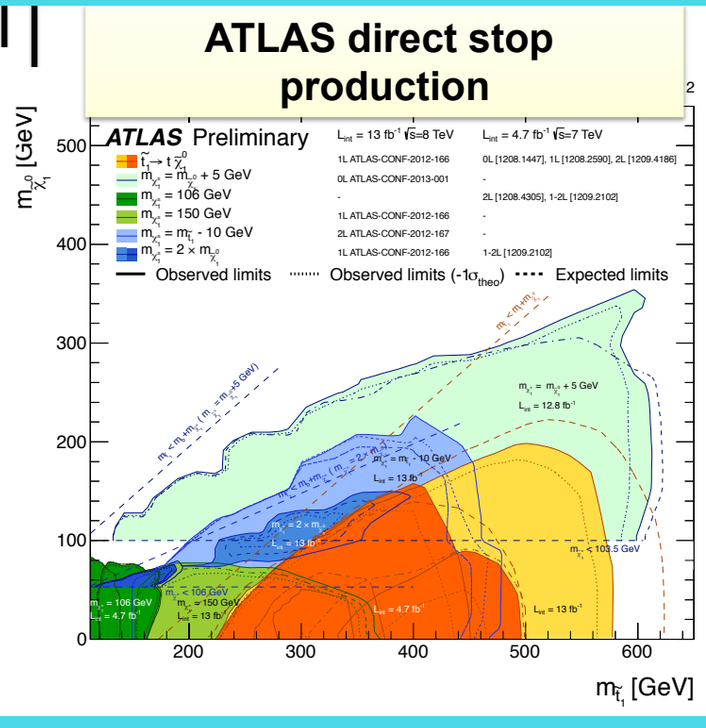


Weakly interacting particles





Strongly interacting particles

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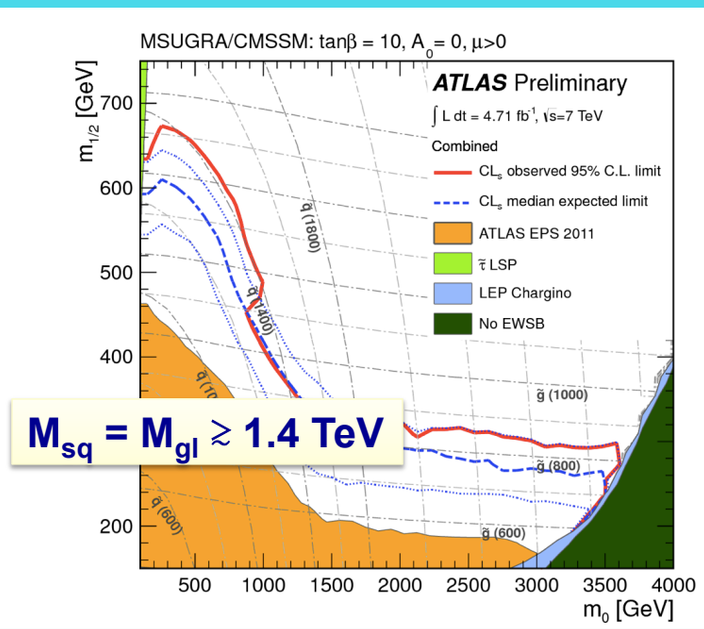
Looking in wrong place?

Search for Supersymmetry @ LHC



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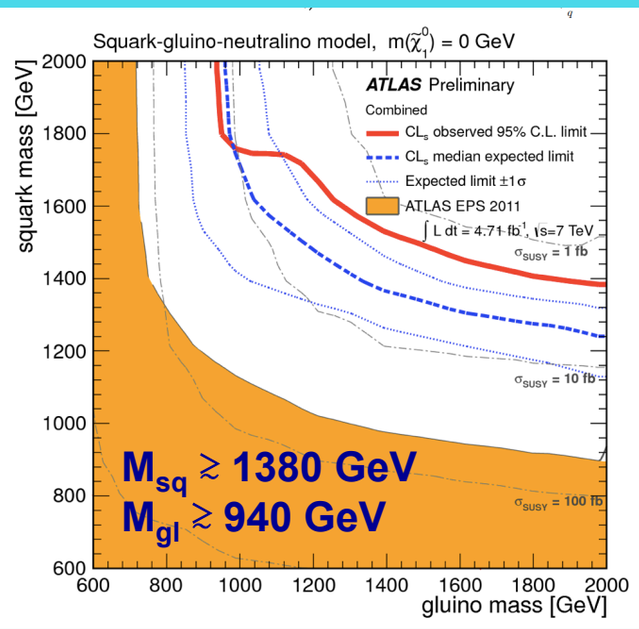

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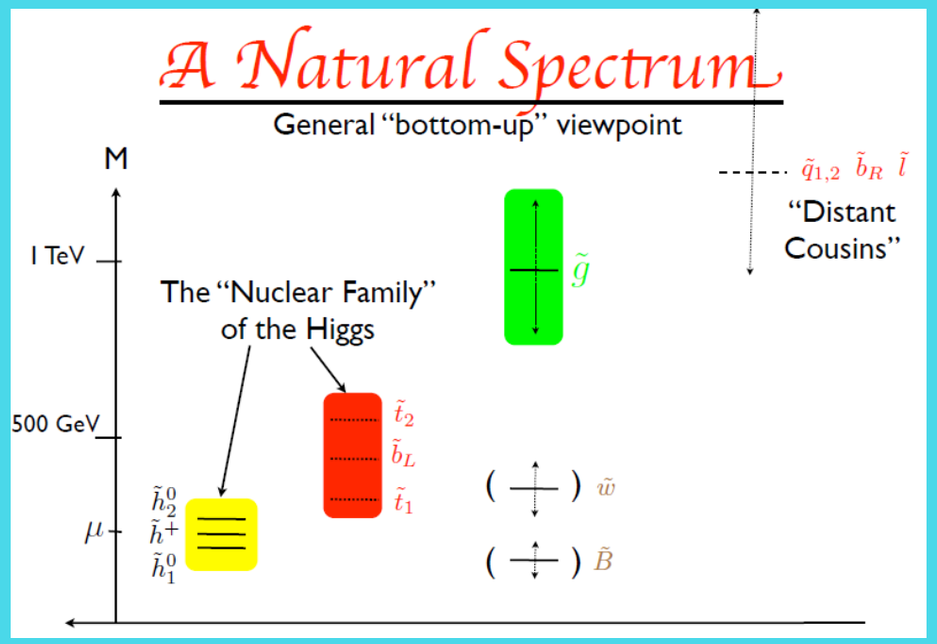

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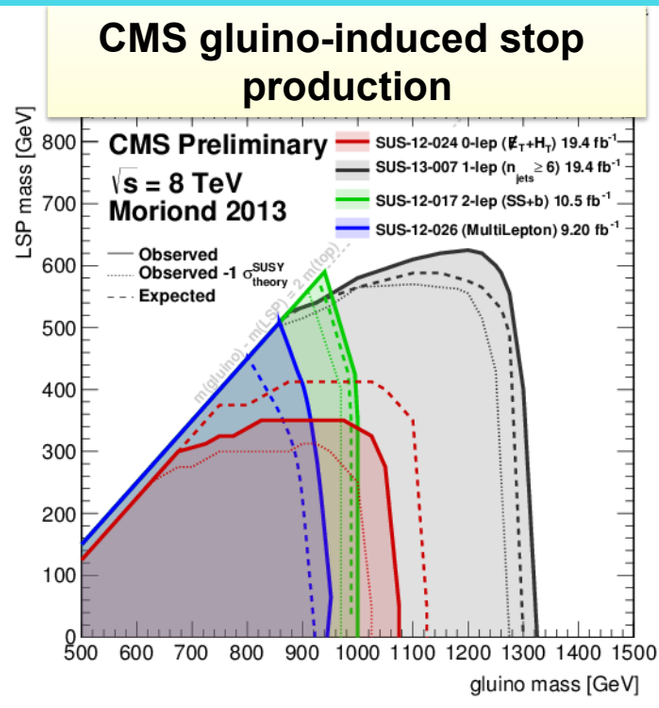
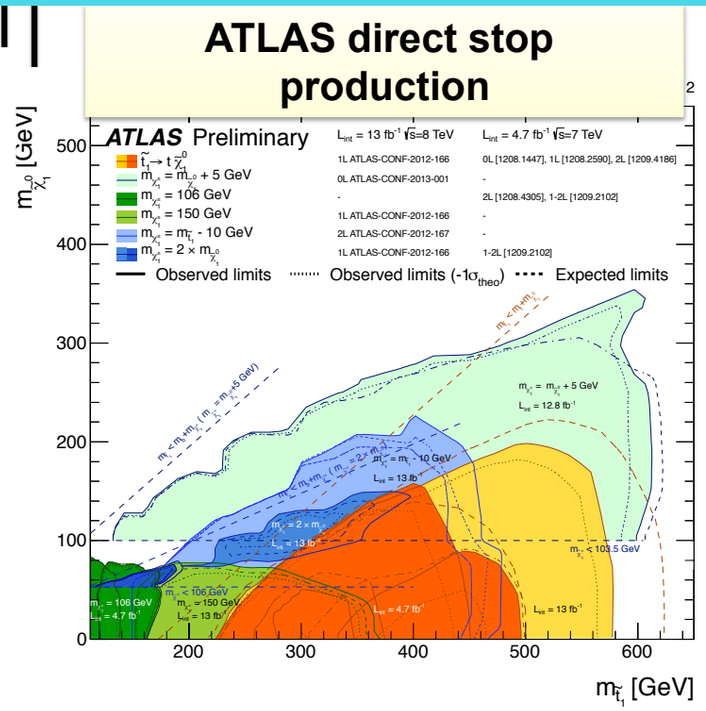




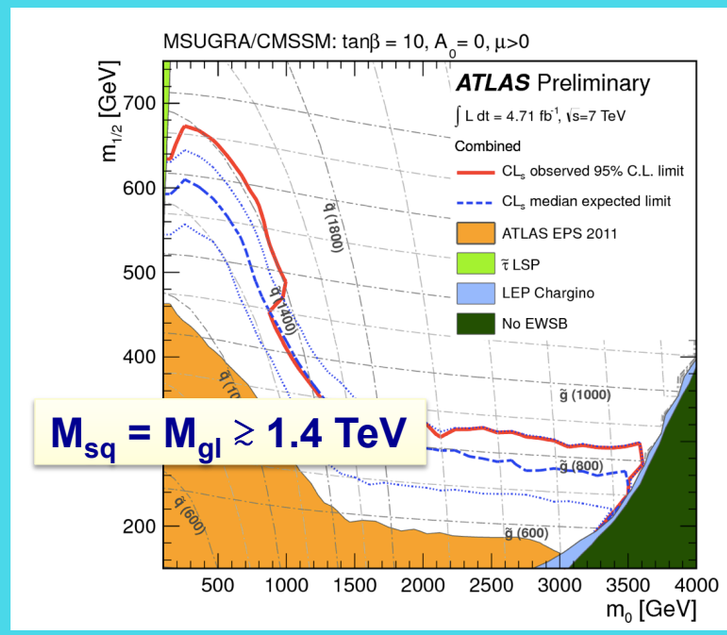
Strongly interacting particles

Tremendous progress of the LHC on SUSY searches is dissapointing so far.

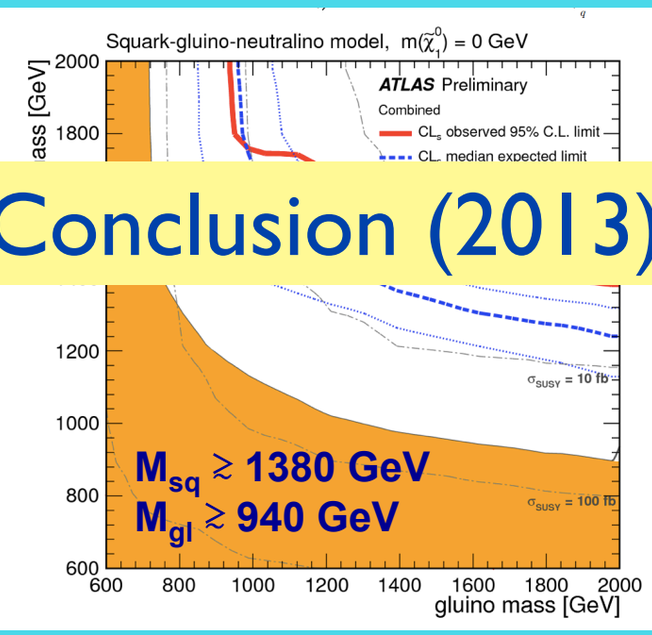
Looking in wrong place?

Still have not reached the the right mass interval?

Search for Supersymmetry @ LHC



$M_{sq} = M_{gl} \gtrsim 1.4$ TeV



$M_{sq} \gtrsim 1380$ GeV
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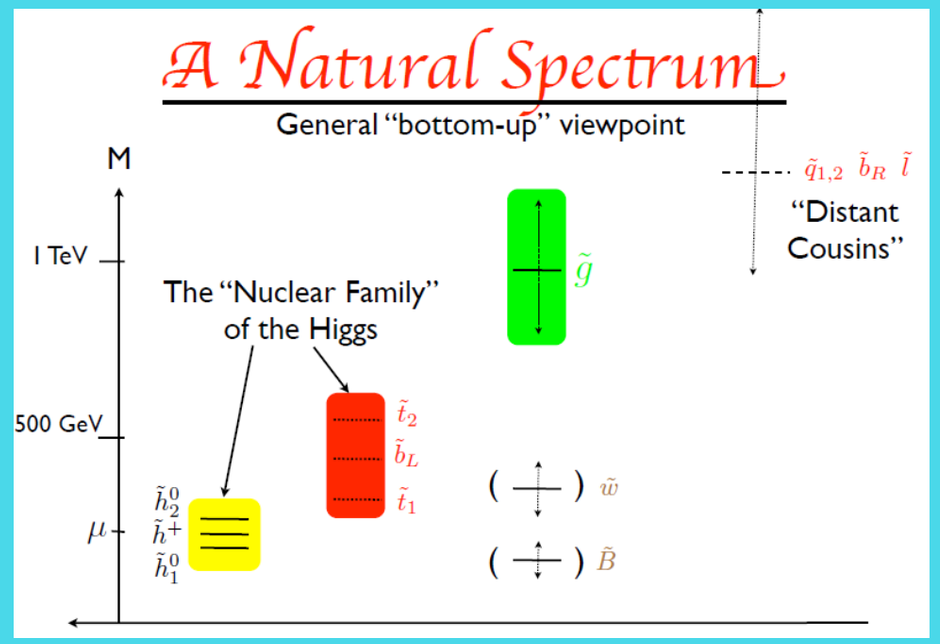
Conclusion (2013)



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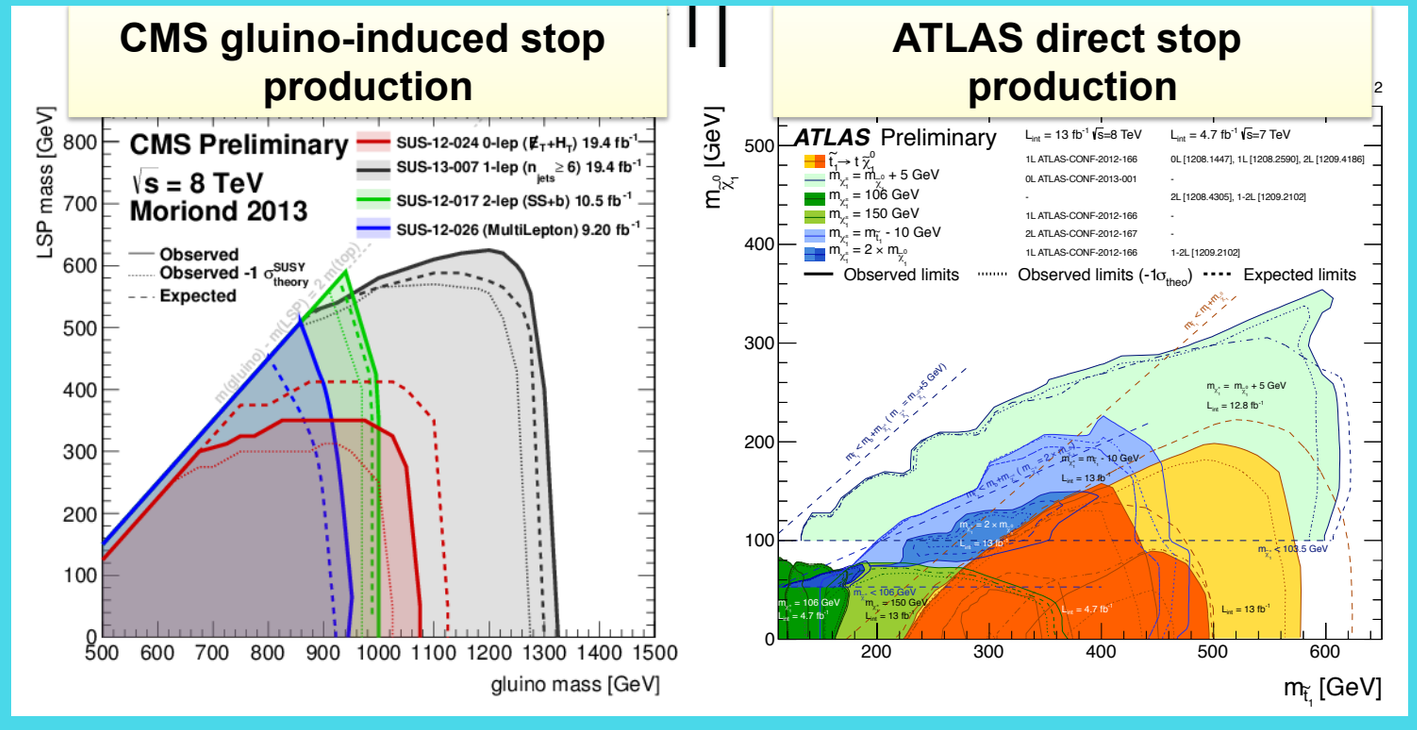

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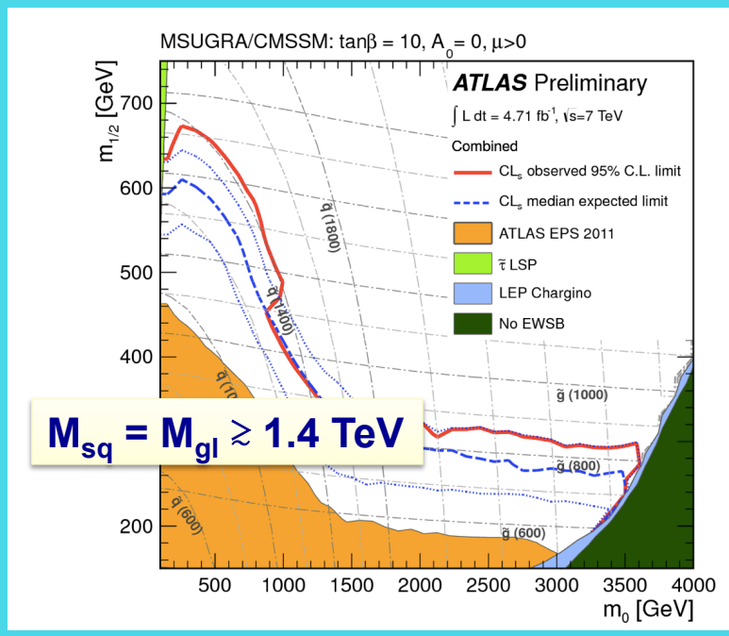
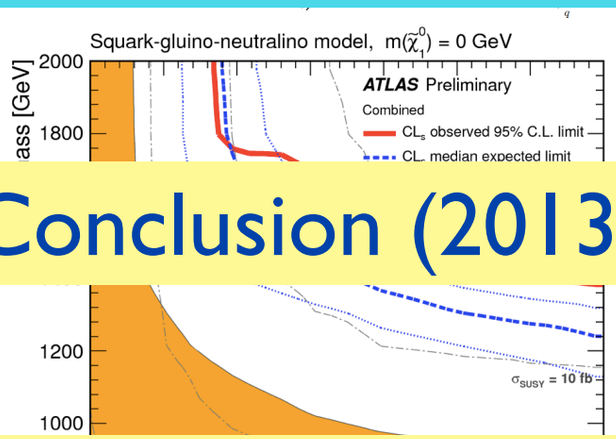
Strongly interacting particles

Search for Supersymmetry @ LHC

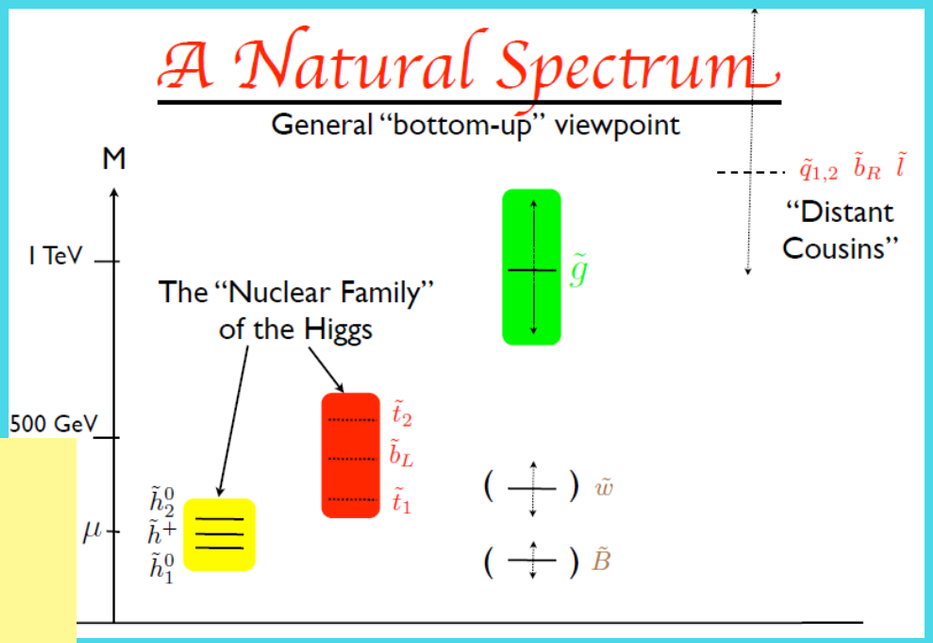


$M_{sq} = M_{gl} \gtrsim 1.4$ TeV



Conclusion (2013)

1.Still no sign of SUSY



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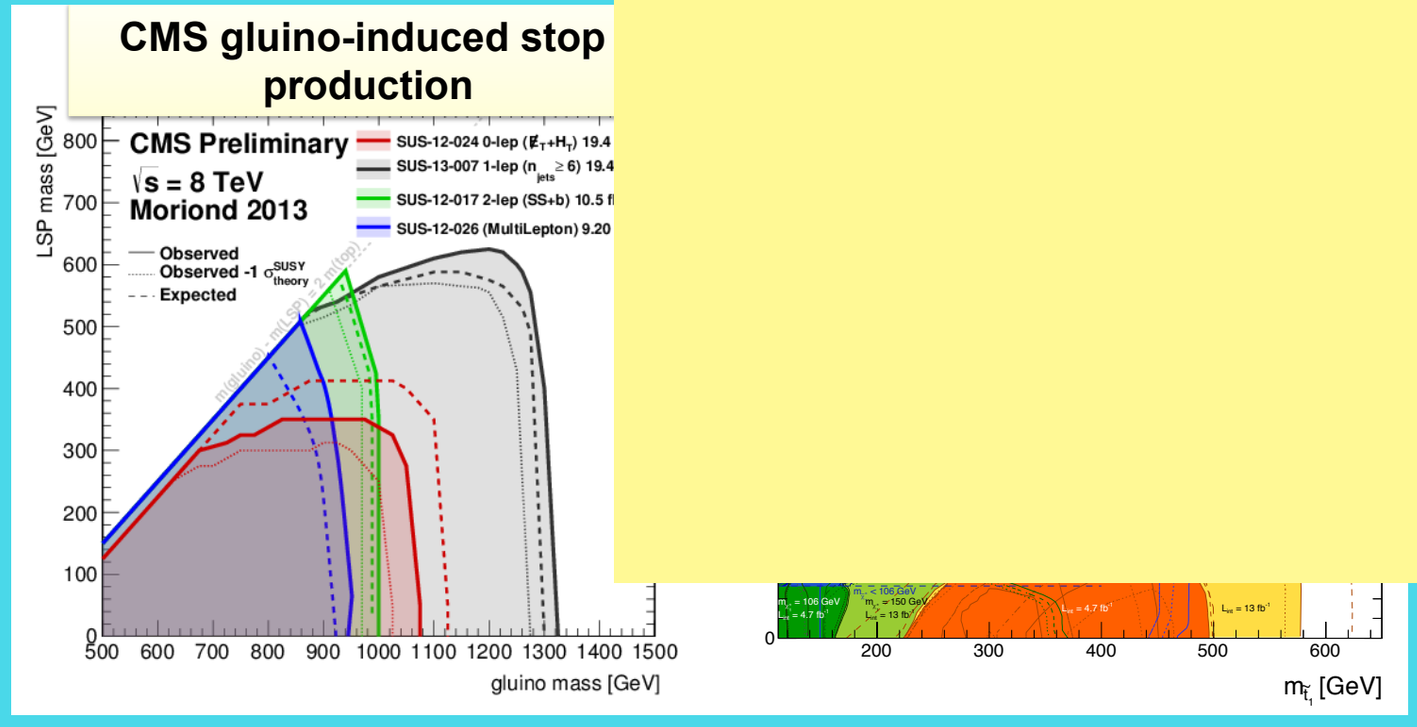

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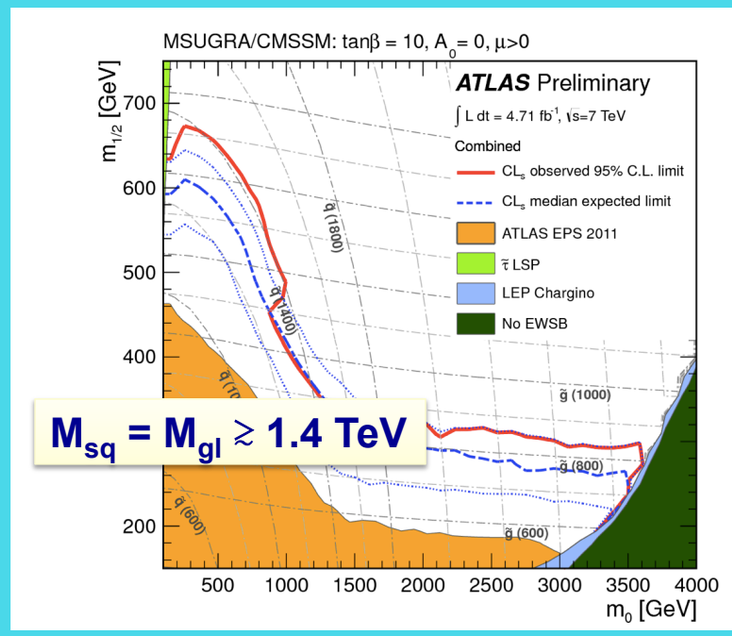
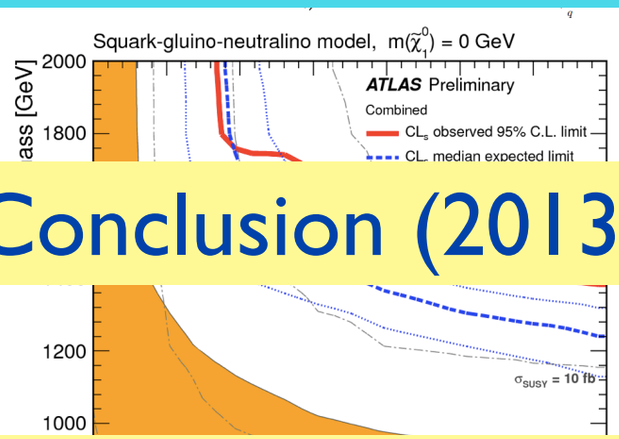
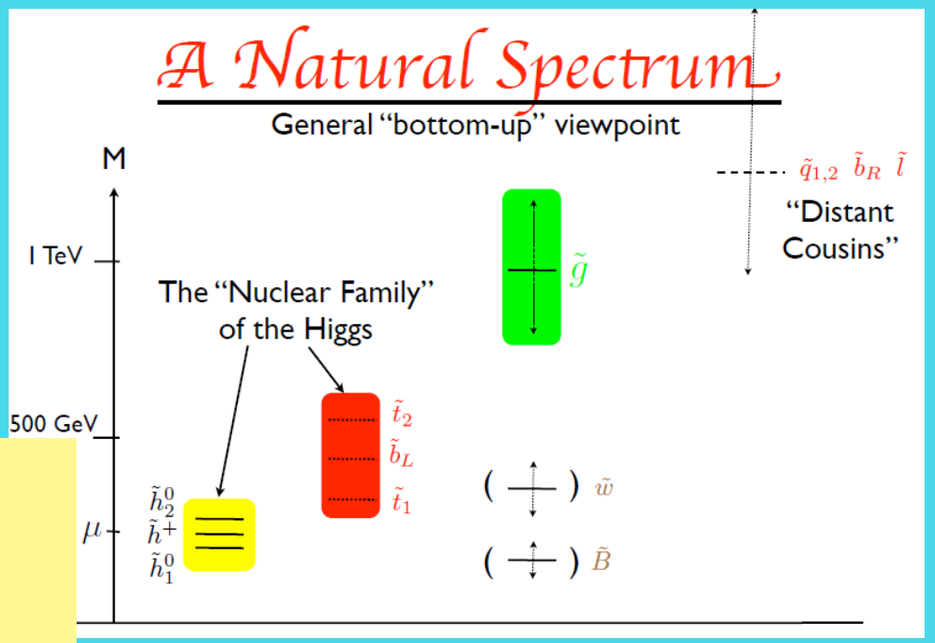


$M_{sq} = M_{gl} \gtrsim 1.4$ TeV

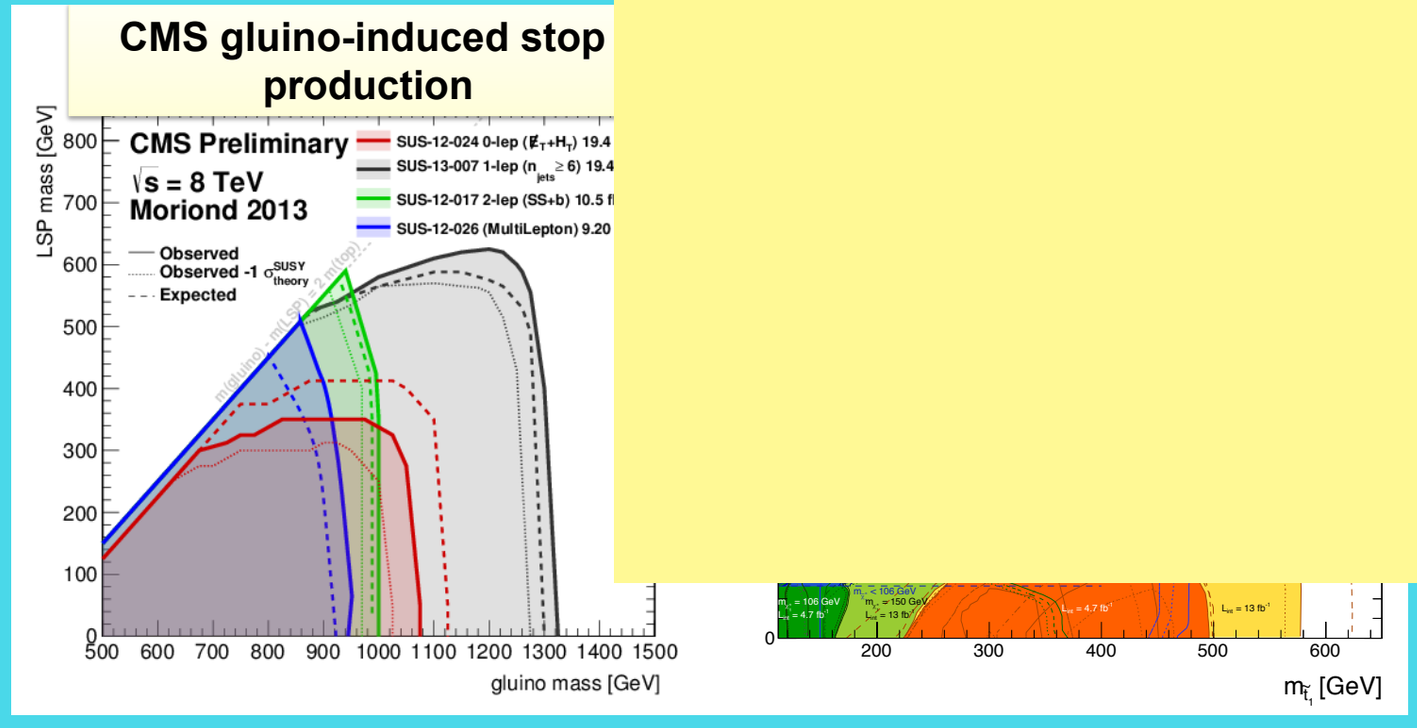


Conclusion (2013)

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



Weakly interacting particles



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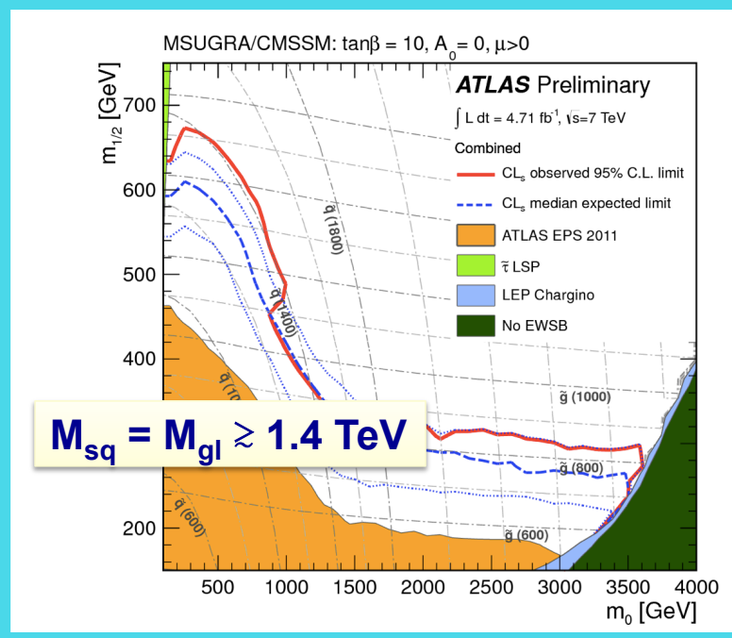
Search for Supersymmetry @ LHC



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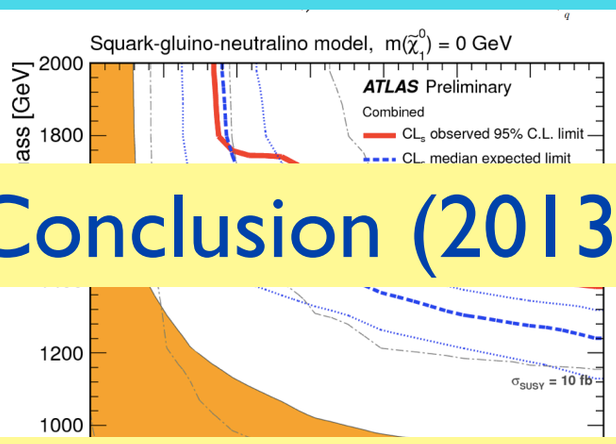
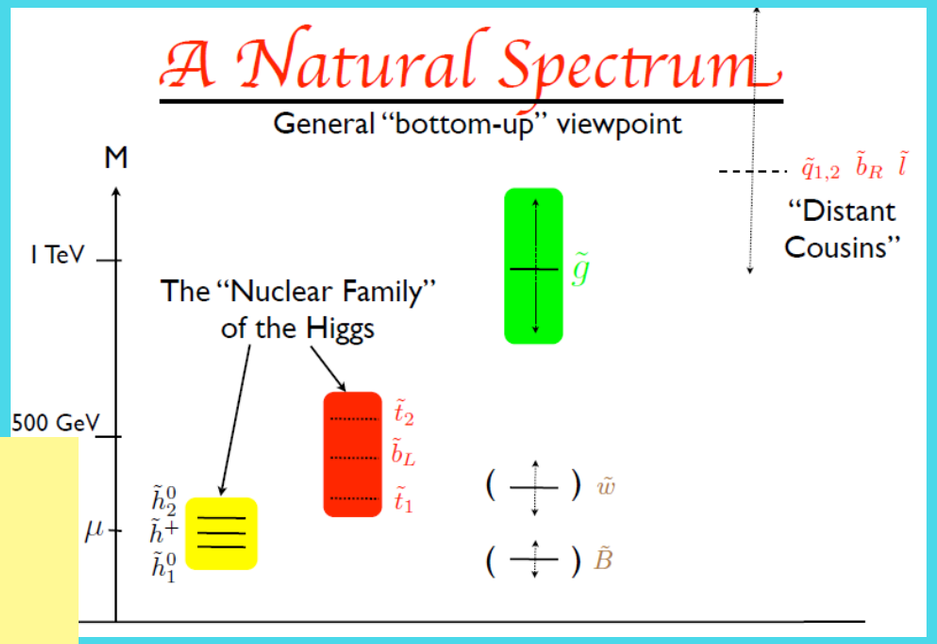
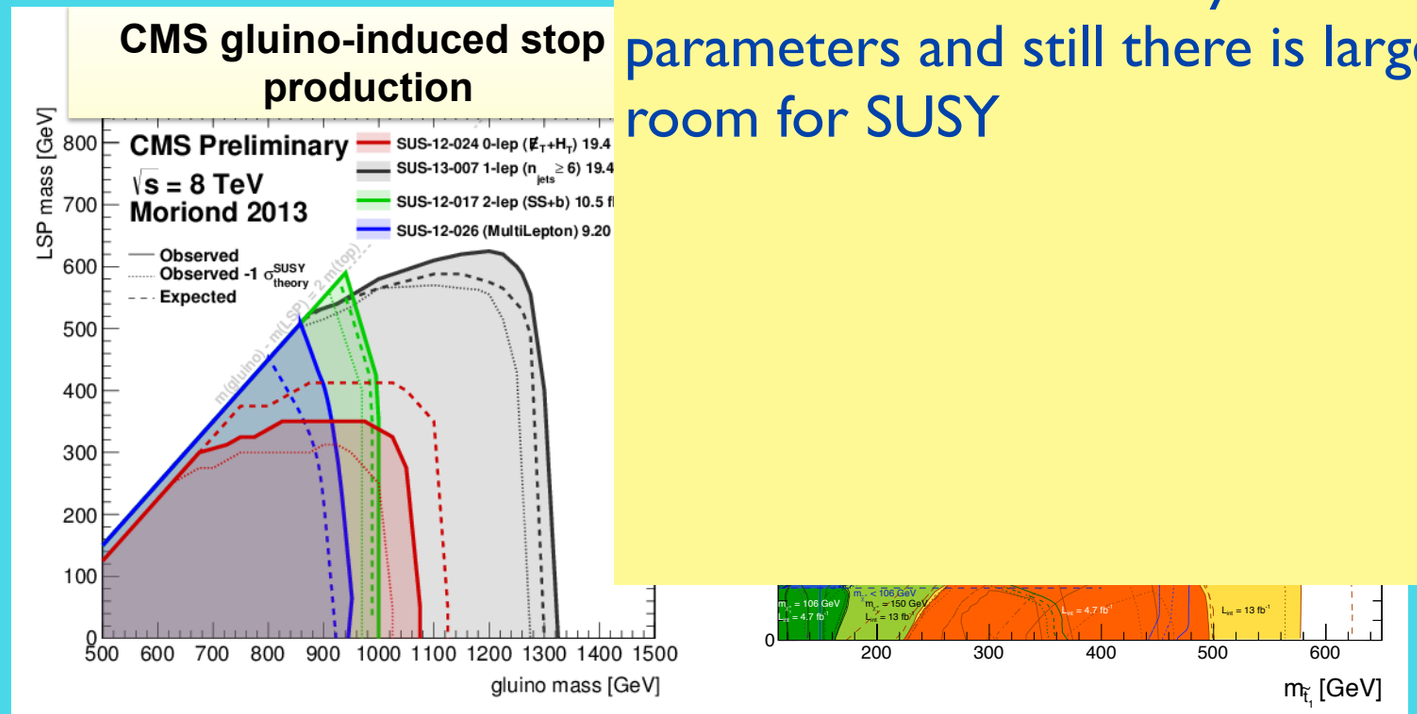


Conclusion (2013)

1. Still no sign of SUSY
2. The obtained constraints are model dependent
3. The models have many parameters and still there is large room for SUSY



Weakly interacting particles



Strongly interacting particles

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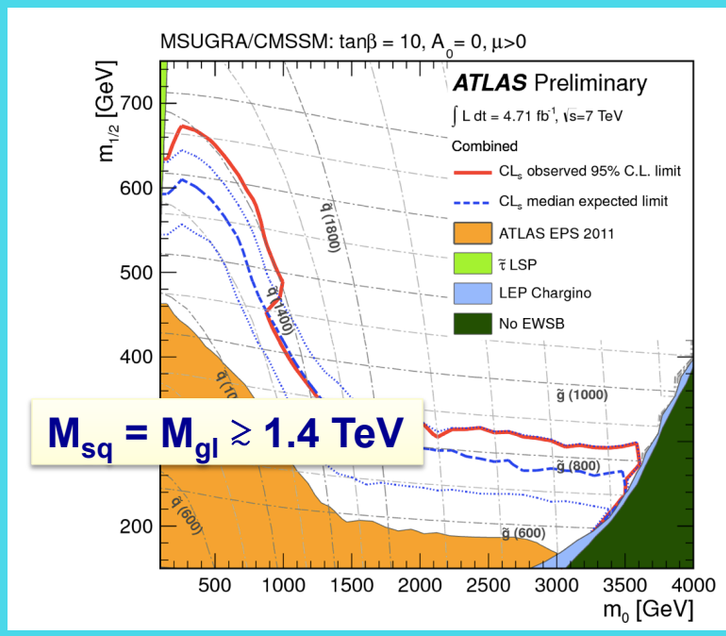
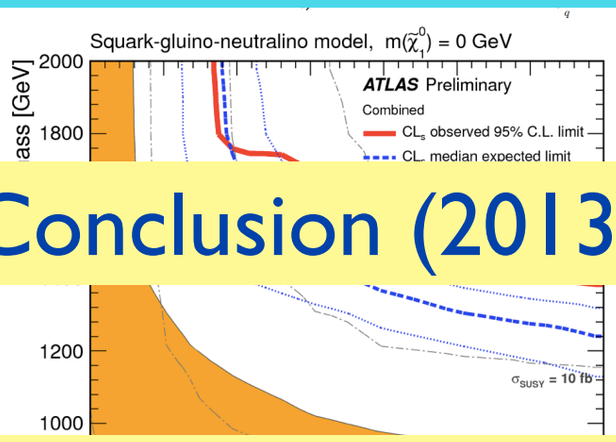
Search for Supersymmetry @ LHC

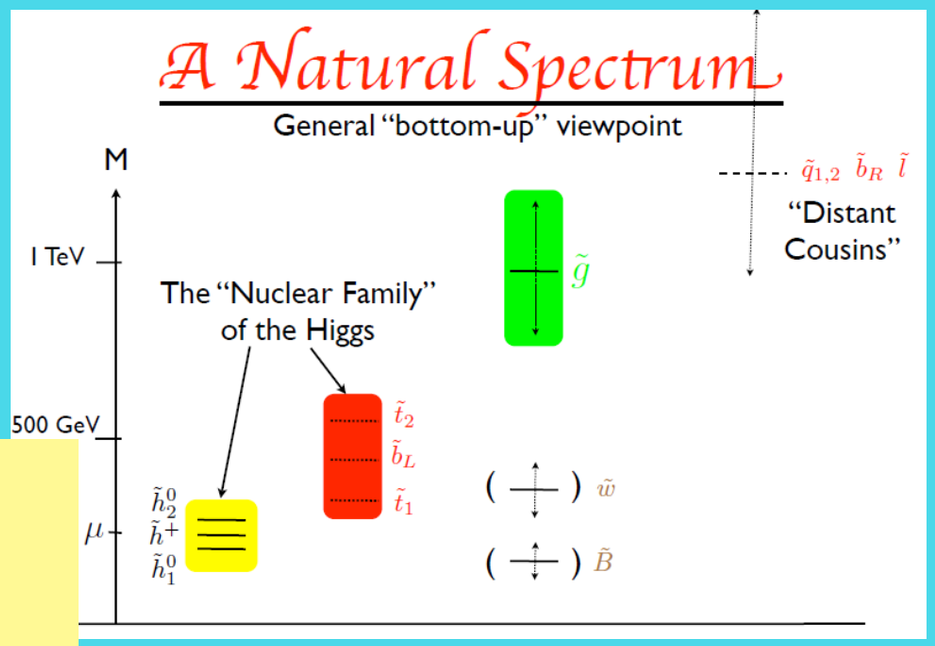


$M_{sq} = M_{gl} \gtrsim 1.4$ TeV



Conclusion (2013)

1. Still no sign of SUSY
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



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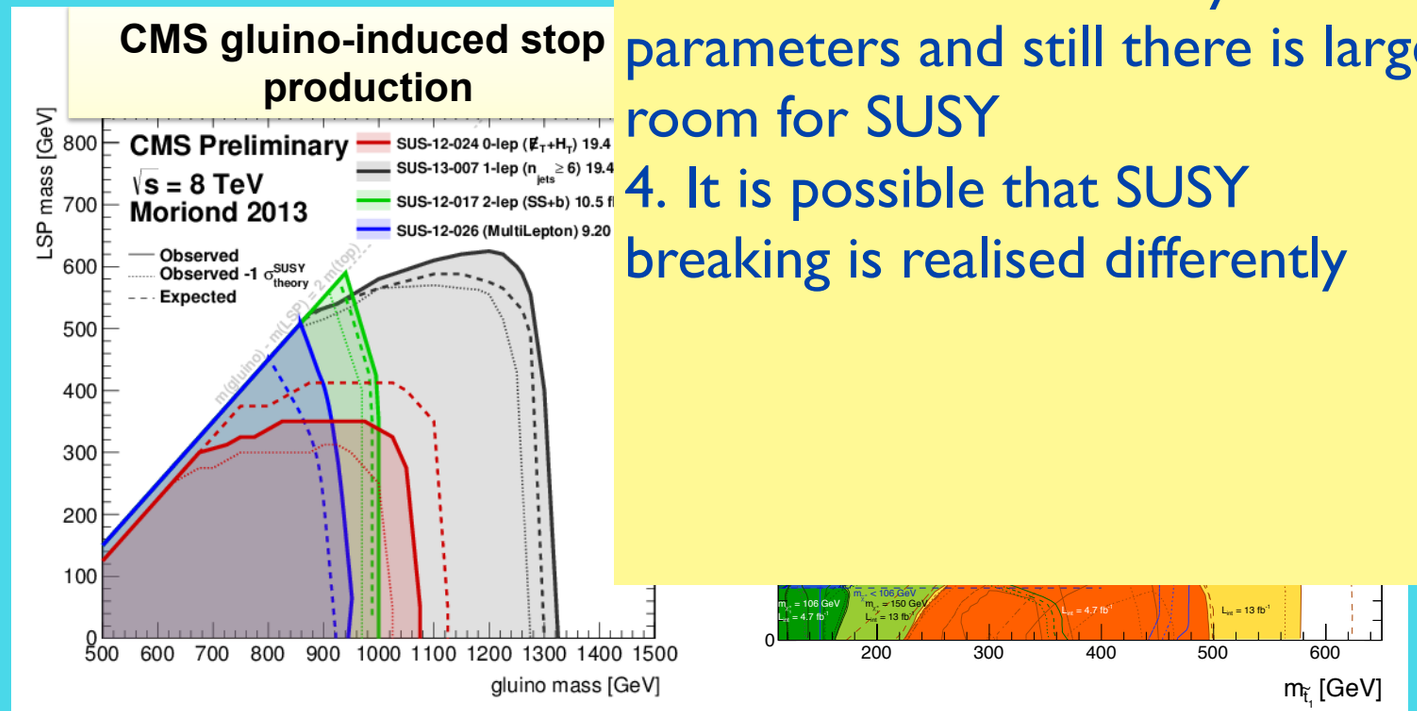

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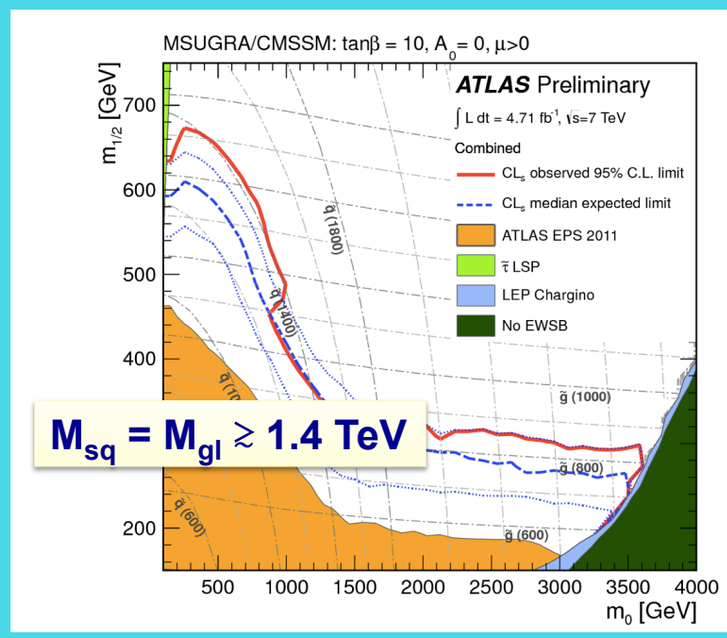
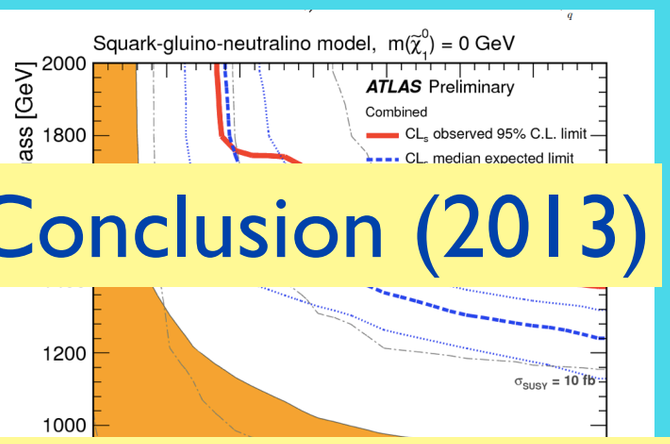
Search for Supersymmetry @ LHC

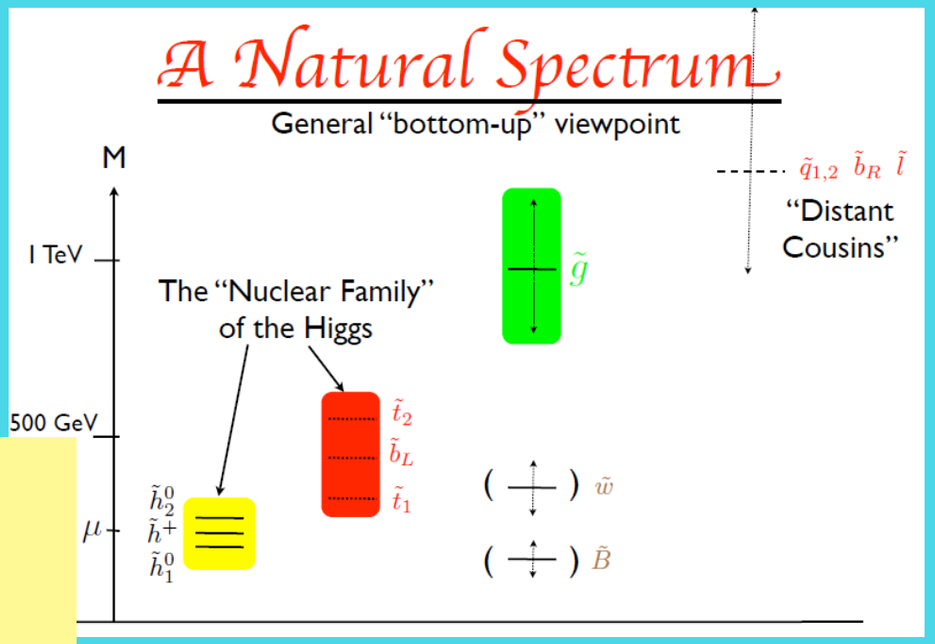


$M_{sq} = M_{gl} \gtrsim 1.4$ TeV

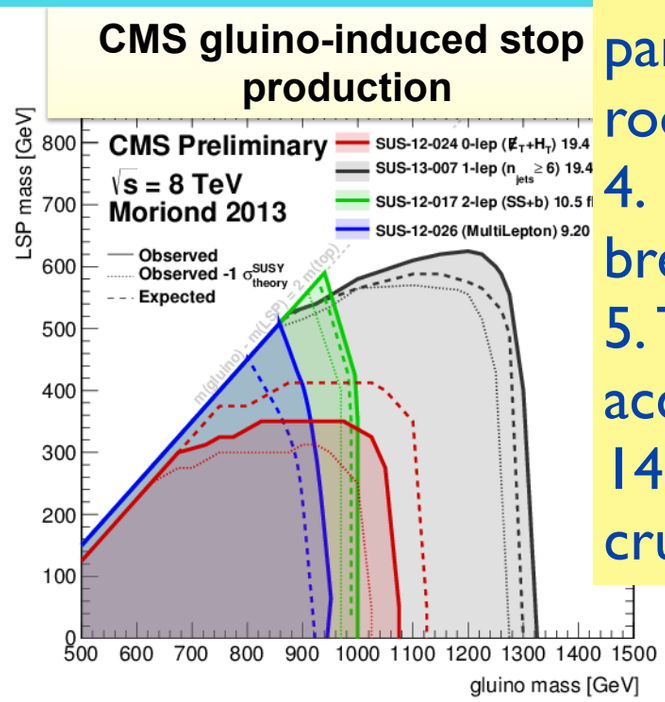


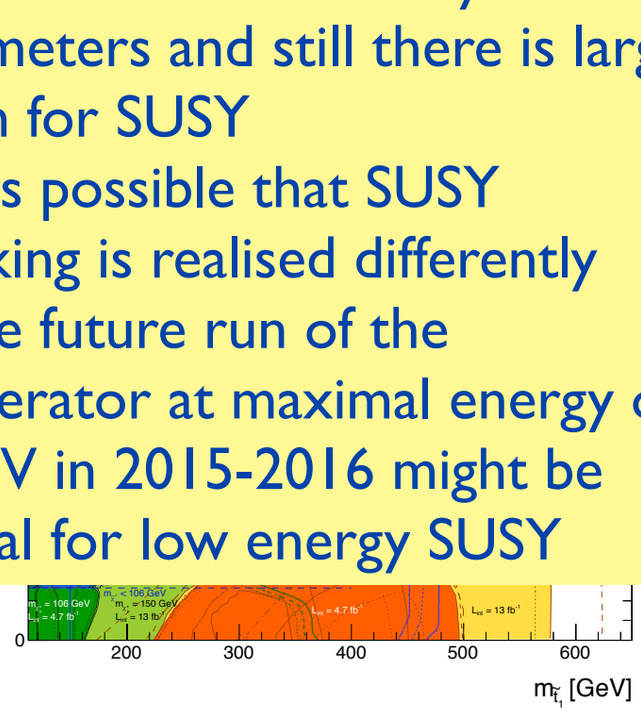
Conclusion (2013)

1. Still no sign of SUSY
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
5. The future run of the accelerator at maximal energy of 14 TeV in 2015-2016 might be crucial for low energy SUSY



Weakly interacting particles





Strongly interacting particles

Tremendous progress of the LHC on SUSY searches is dissapointing so far.

Looking in wrong place?

Still have not reached the the right mass interval?

Forward into the Future

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The research program for the coming years

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