Particle physics: present and prospects

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The Standard Theory

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons ($\underline{3}$x$\underline{2}$, $\underline{3}$x$\underline{1}$, $\underline{1}$x$\underline{2}$, $\underline{1}$x$\underline{1}$)
- Brout-Englert-Higgs mechanism of spontaneous EW symmetry breaking -> Higgs boson
- CKM and PMNS mixing of flavours
- CP violation via phase factors
- Confinement of quarks and gluons inside hadrons
- Baryon and lepton number conservation
- CPT invariance -> existence of antimatter

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- Extra families of quarks and leptons
- Presence or absence of right-handed neutrino
- Majorana or Dirac nature of neutrino
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The ST principles allow:

Extra families of quarks and leptons	Seems to be excluded by exp
Presence or absence of right-handed neutrino	Still unclear
Majorana or Dirac nature of neutrino	Still unclear
Extra Higgs bosons	Still unclear

Main questions to the ST

- Is it self consistent ?
- Does it describe all experimental data?
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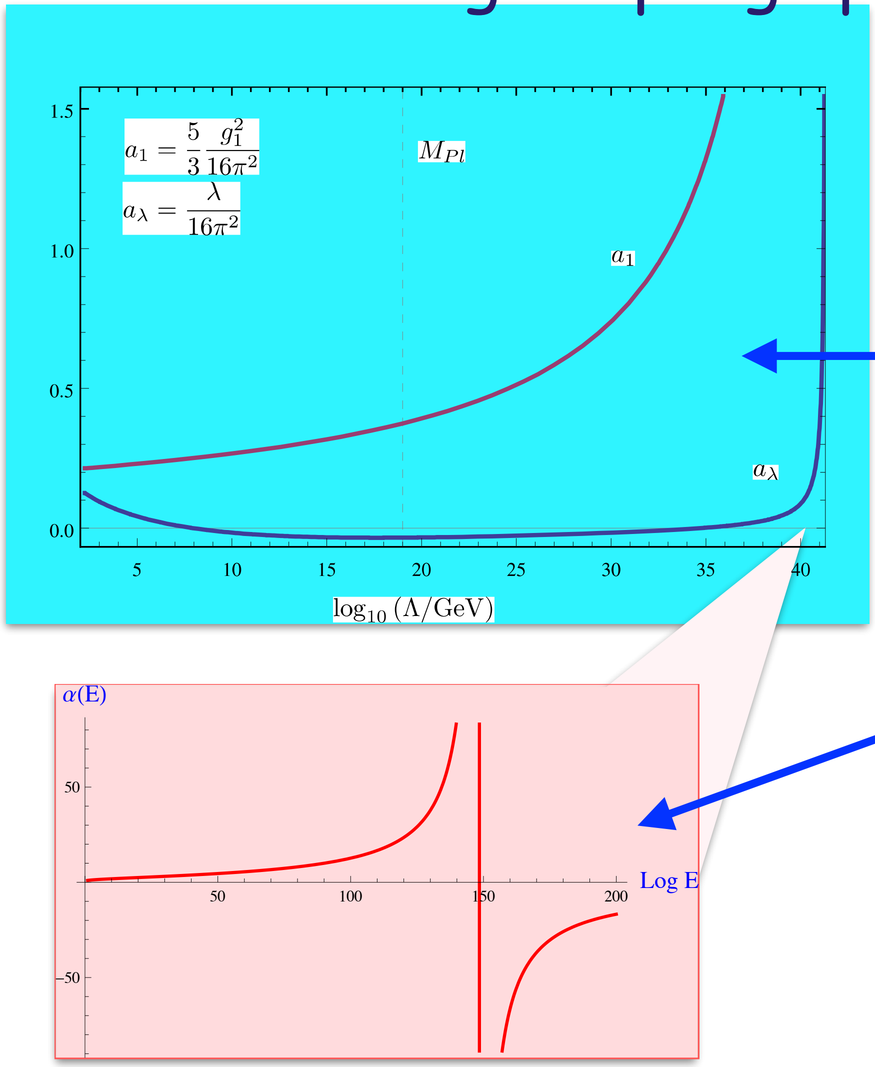
- how CP violation occurs in the Universe?
- how to protect the SM from would be heavy scale physics?

Is the SM consistent quantum field theory?

- The running couplings possess the Landau ghost poles at high energies



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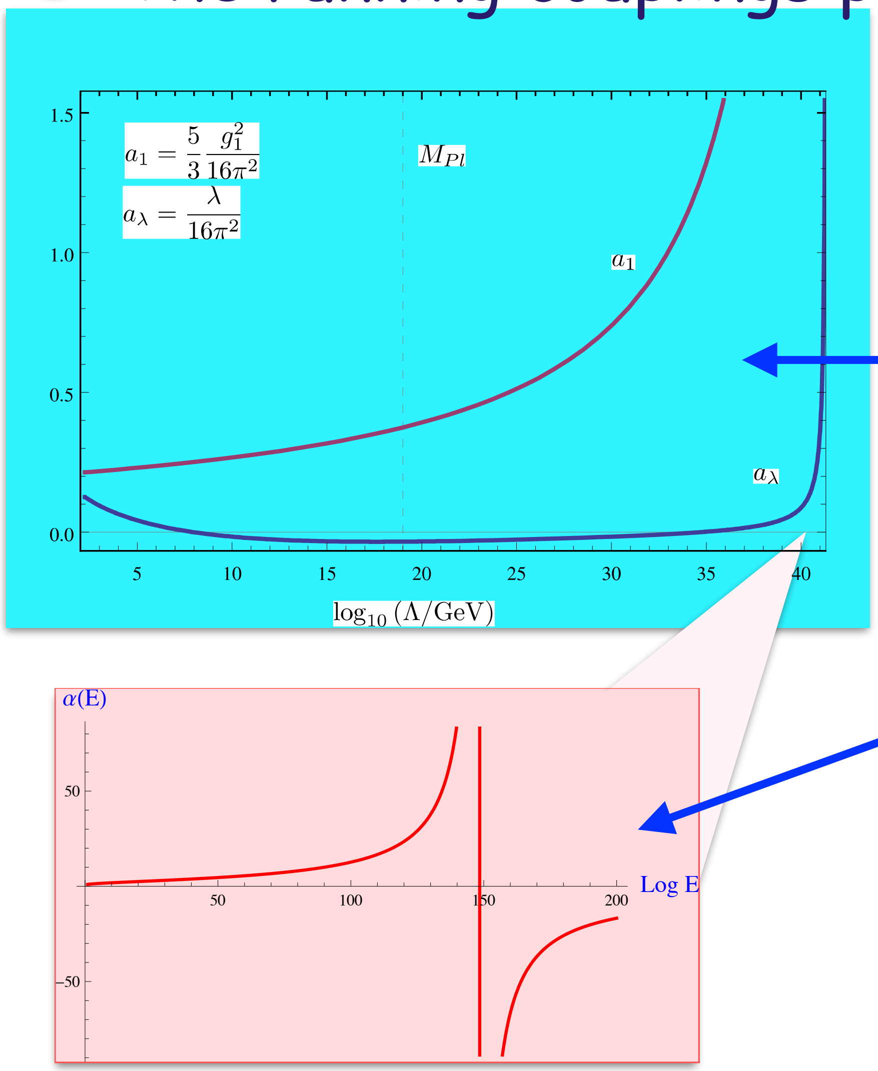

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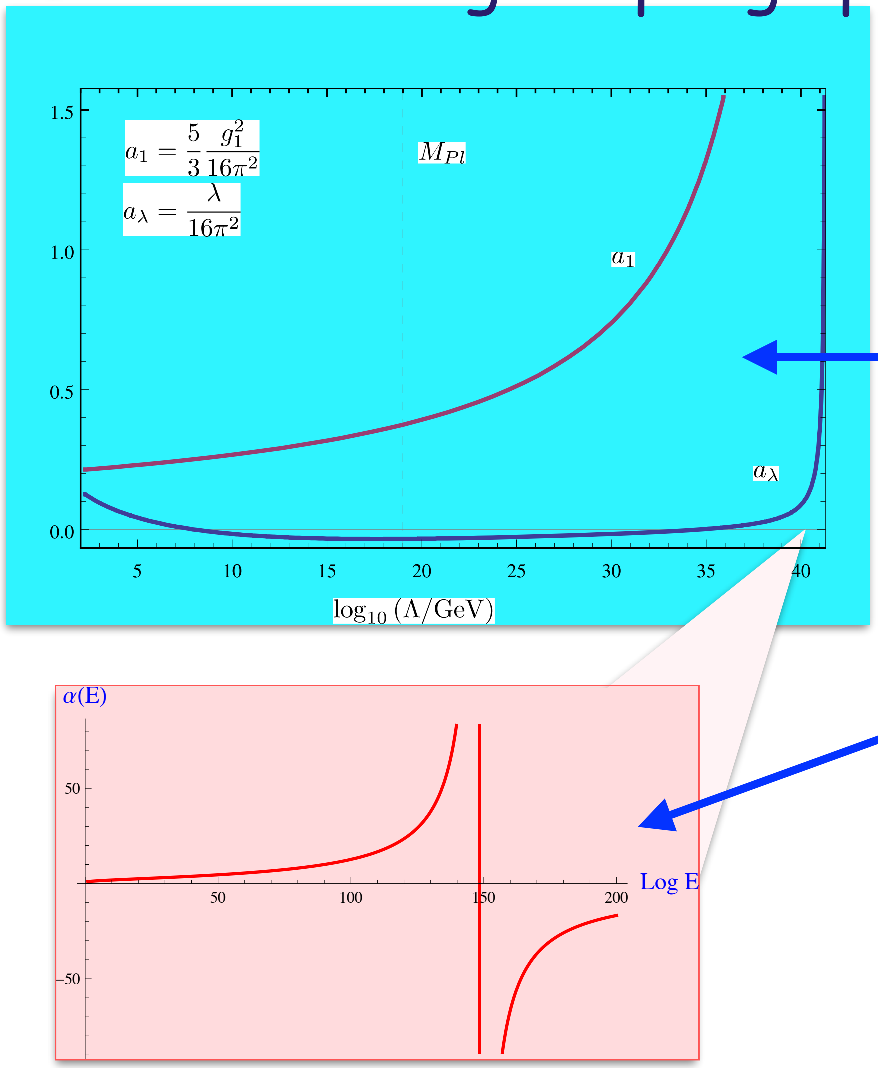

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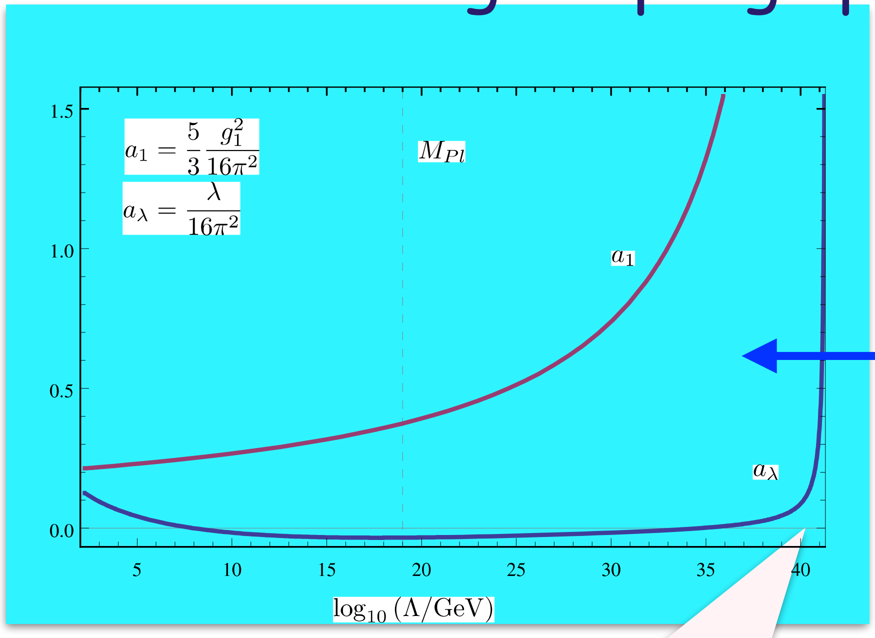

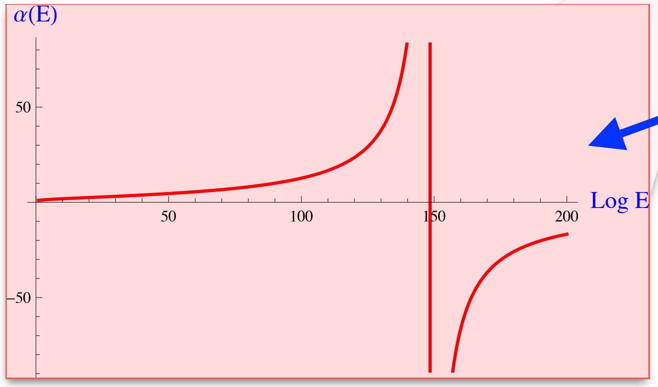

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- requires modification of the ST at VERY high energies

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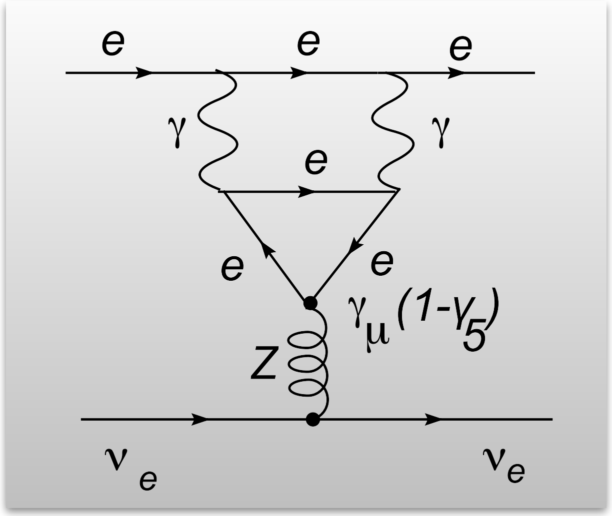

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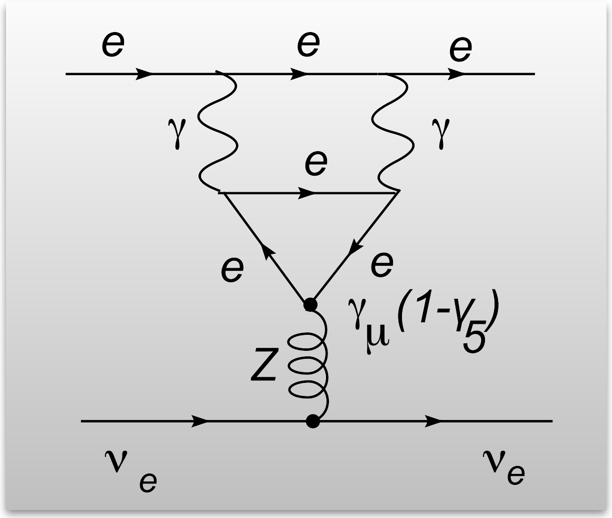

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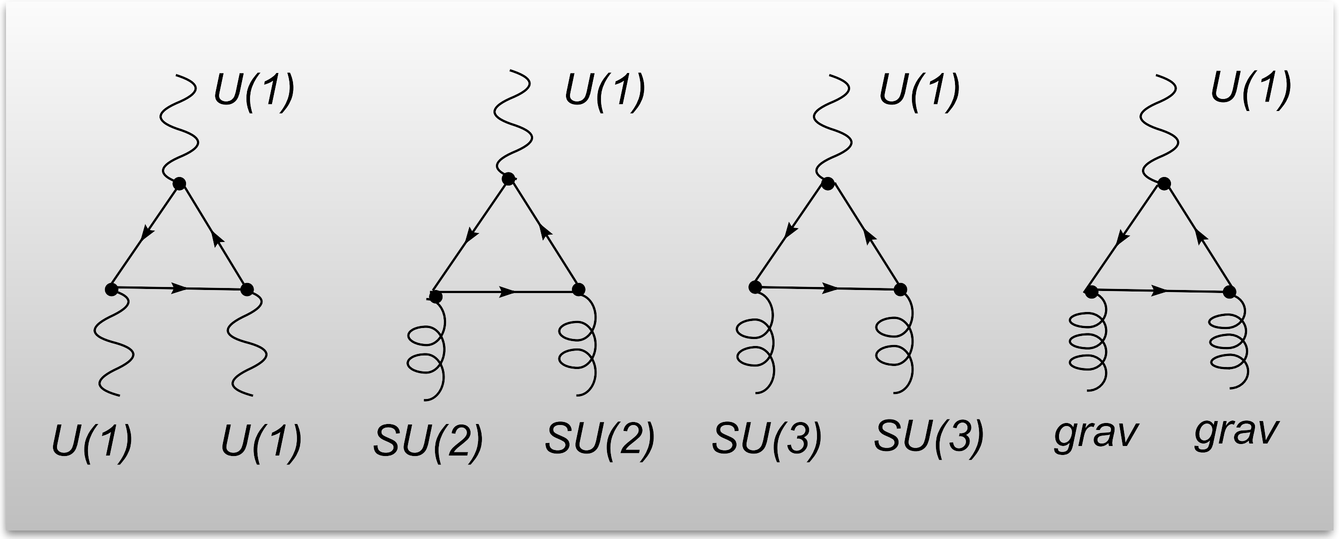

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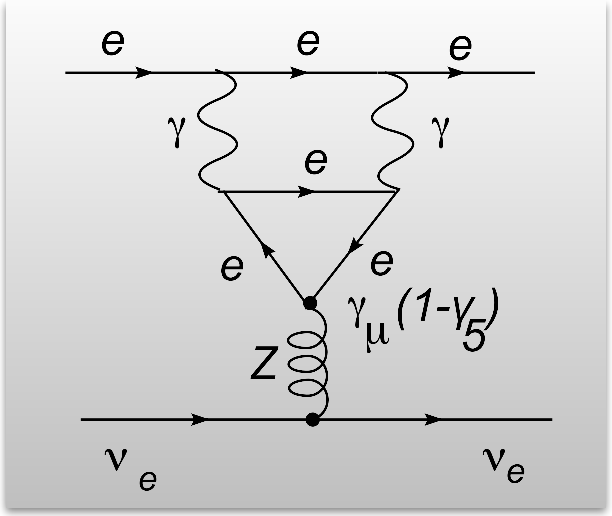

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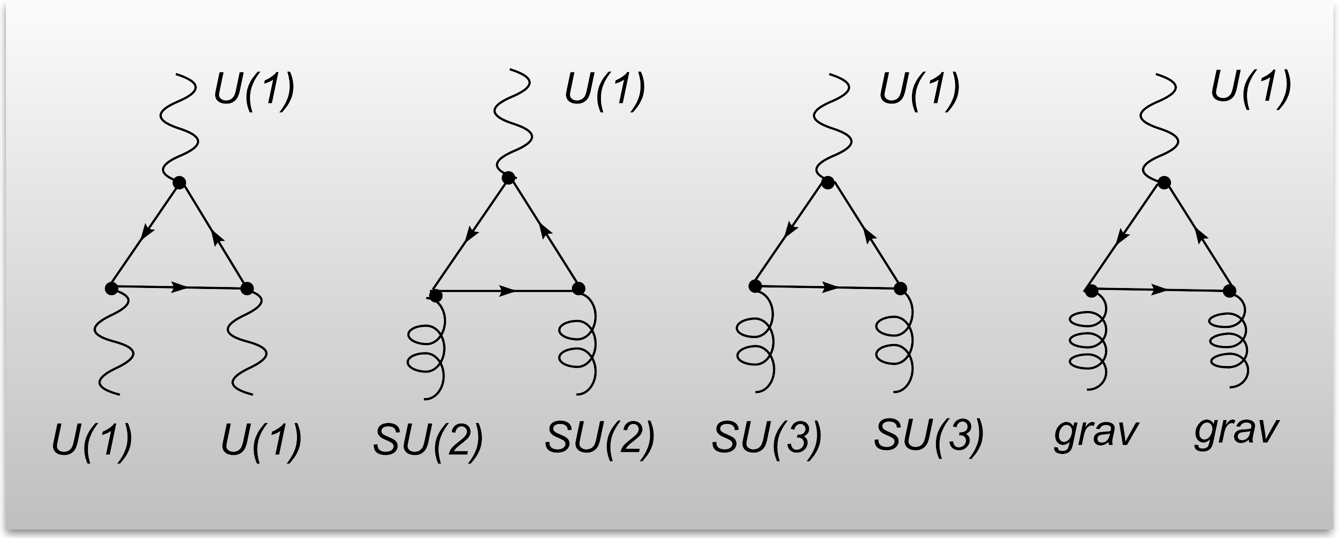

$$TrY^3 = \; = 3\left[(\frac{1}{3})^3+(\frac{1}{3})^3-(\frac{4}{3})^3-(-\frac{2}{3})^3\right]+(-1)^3+(-1)^3-(-2)^3=0.$$

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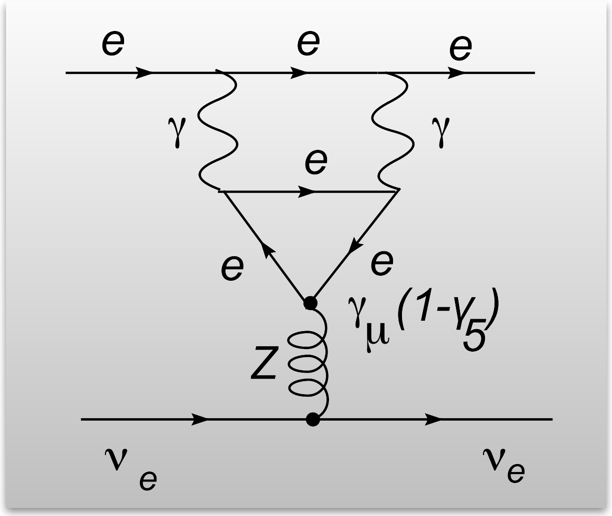

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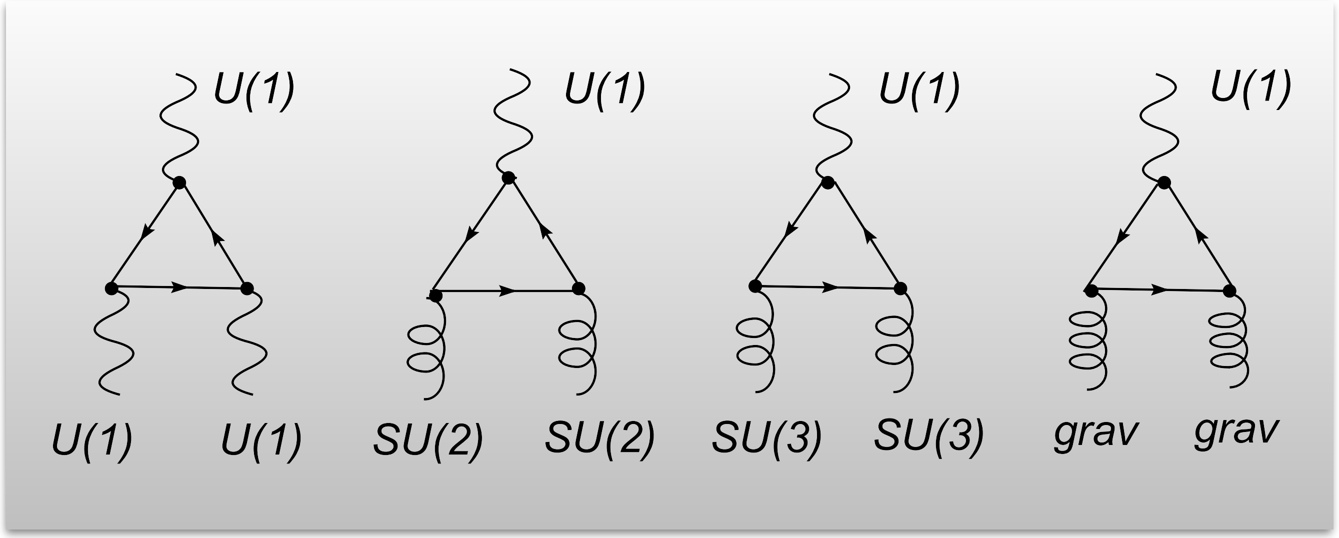

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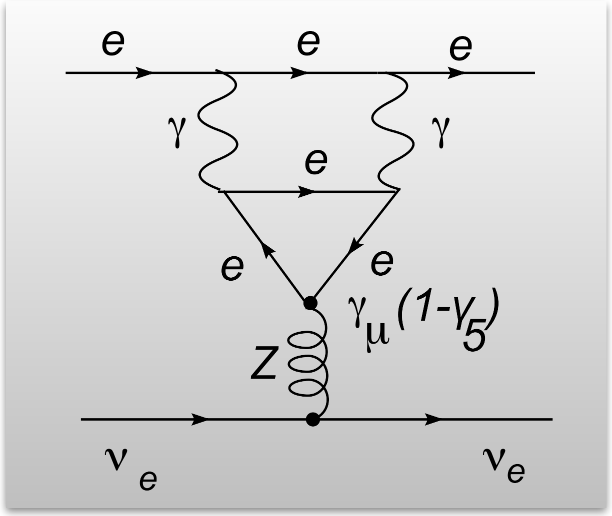

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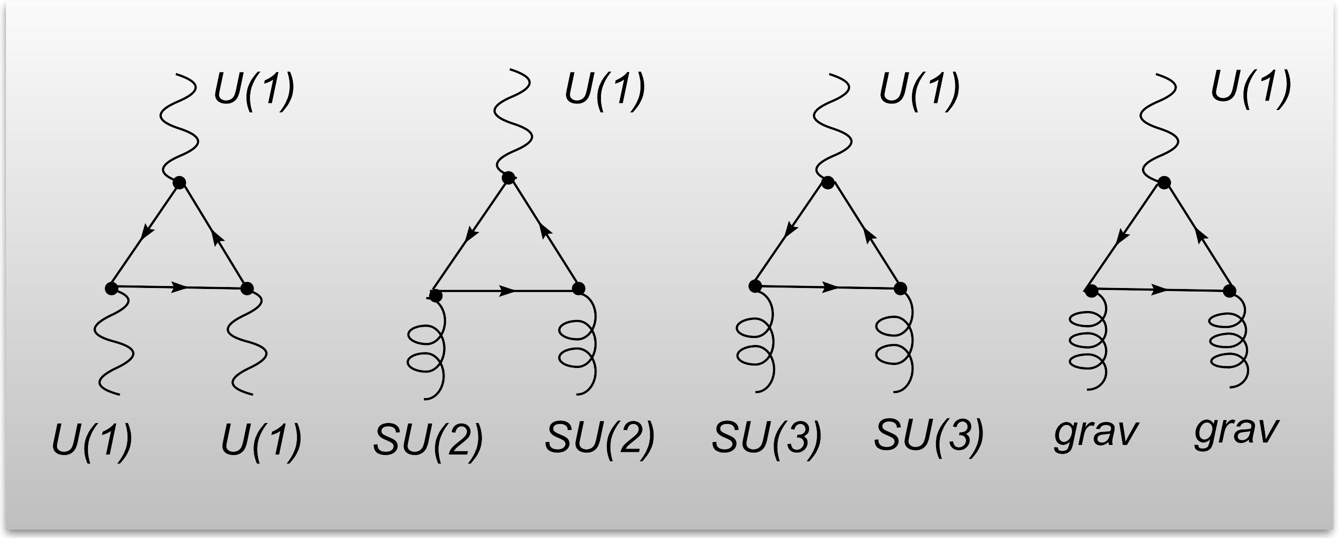

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- cancellation of anomalies requires quark-lepton symmetry
- this is a hint towards the Grand Unified Theories

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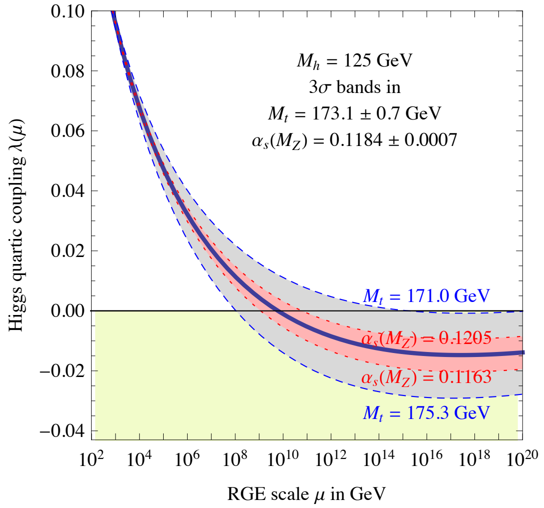

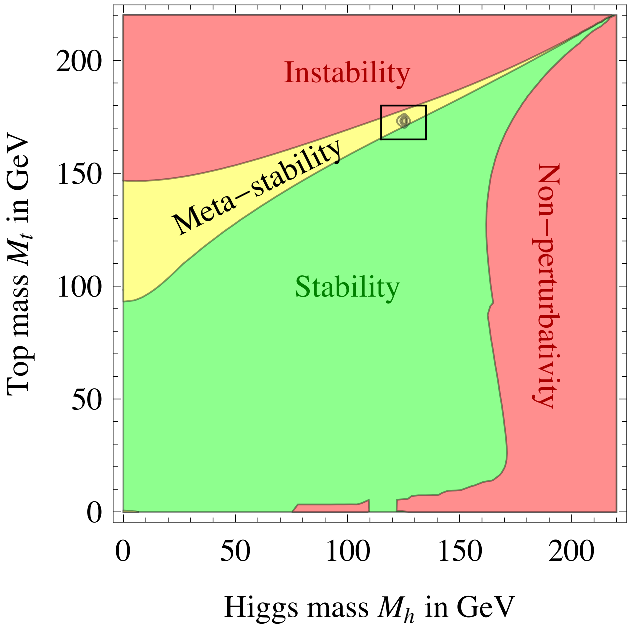

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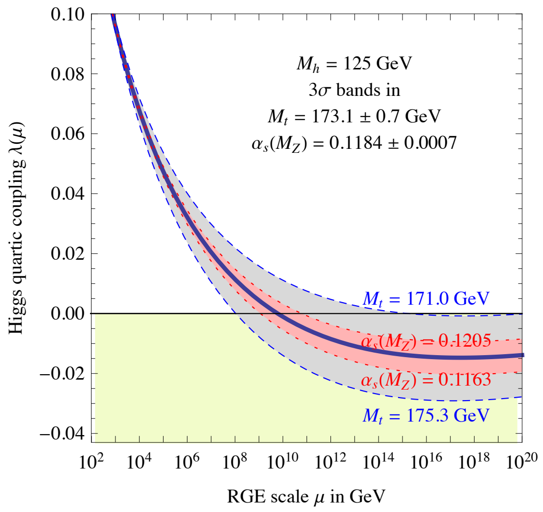

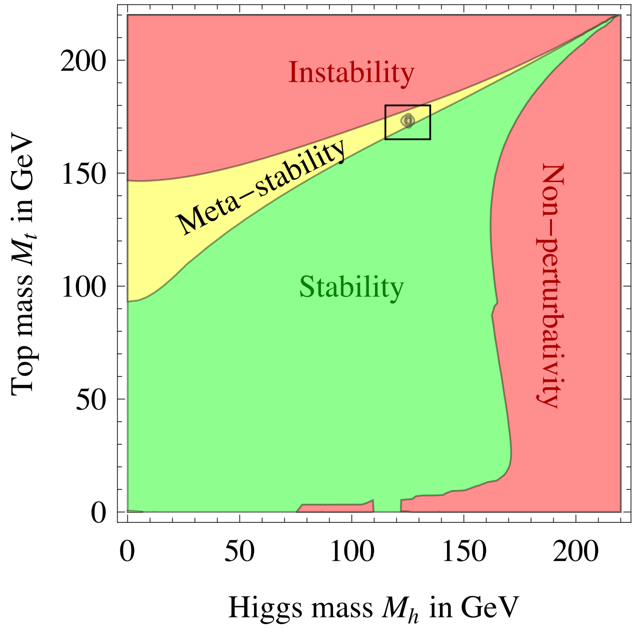

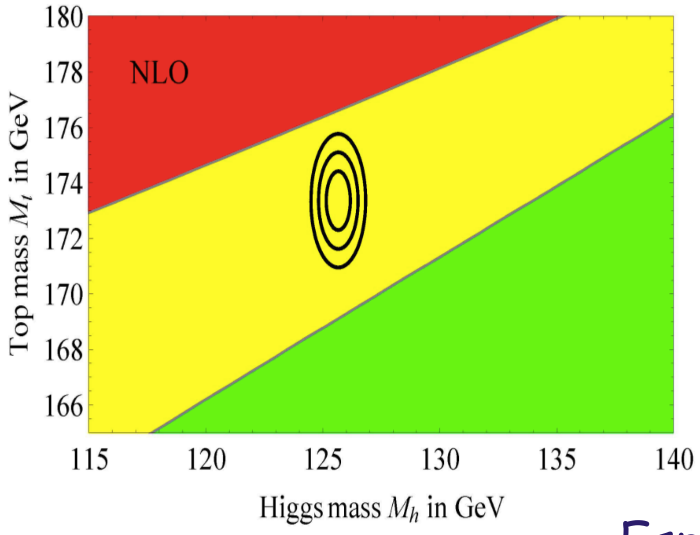

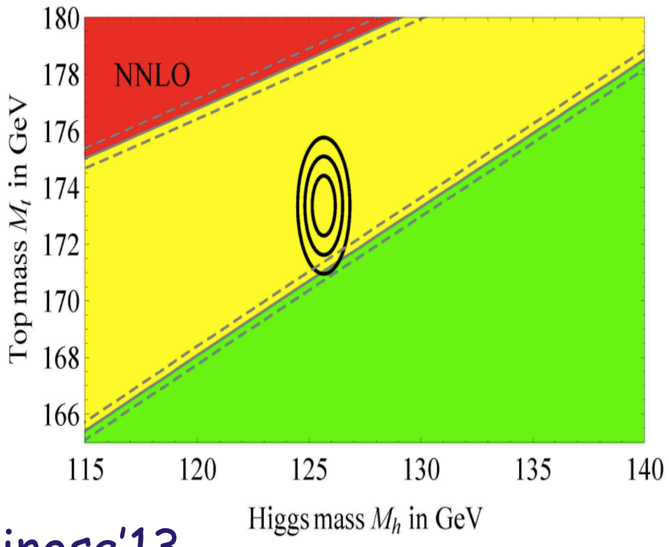

Espinosa'13

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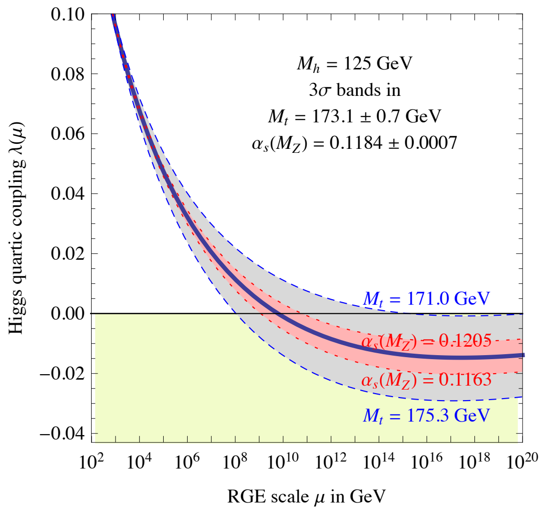

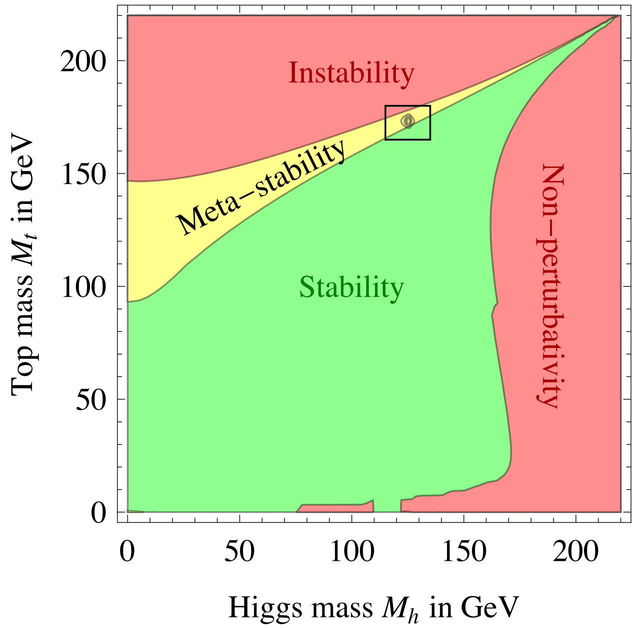

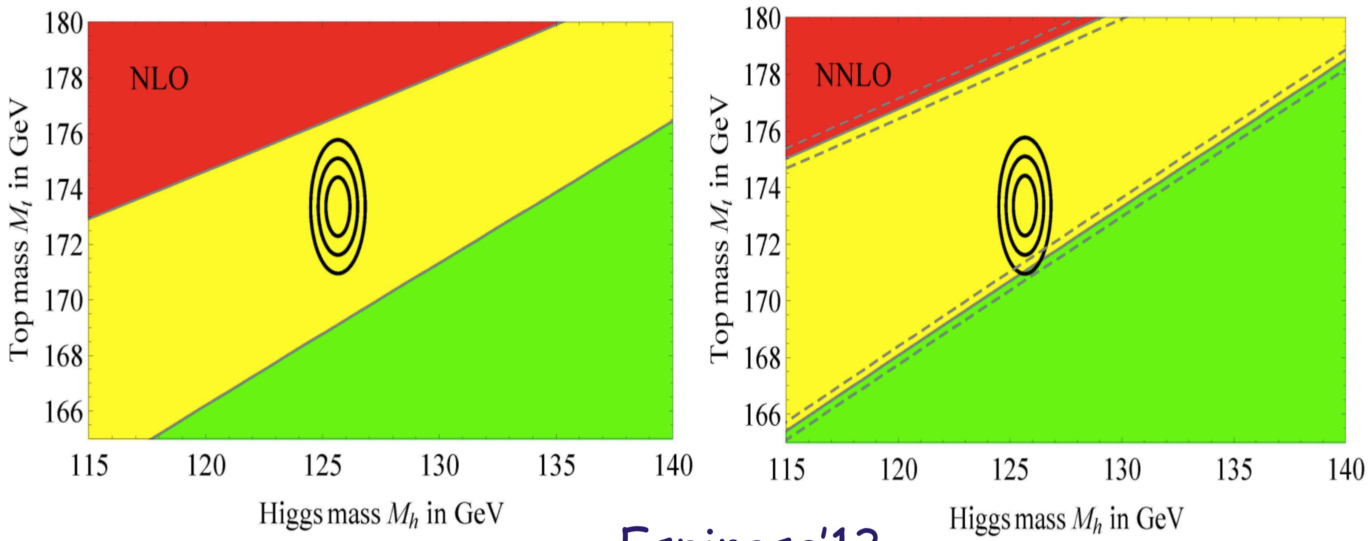

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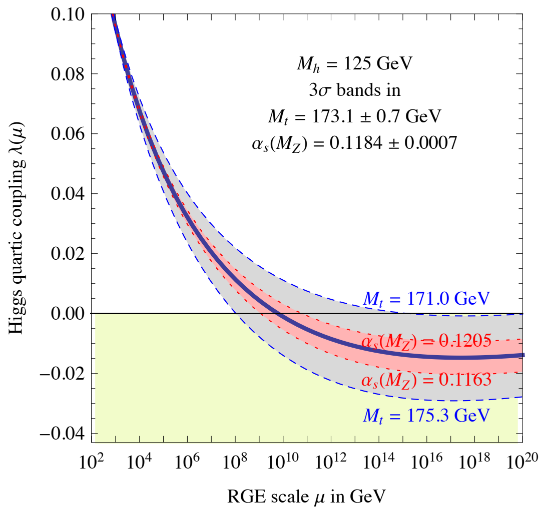

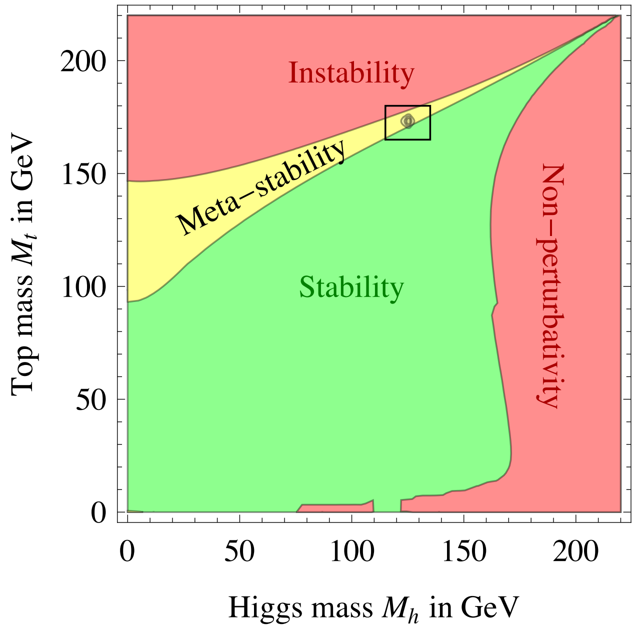

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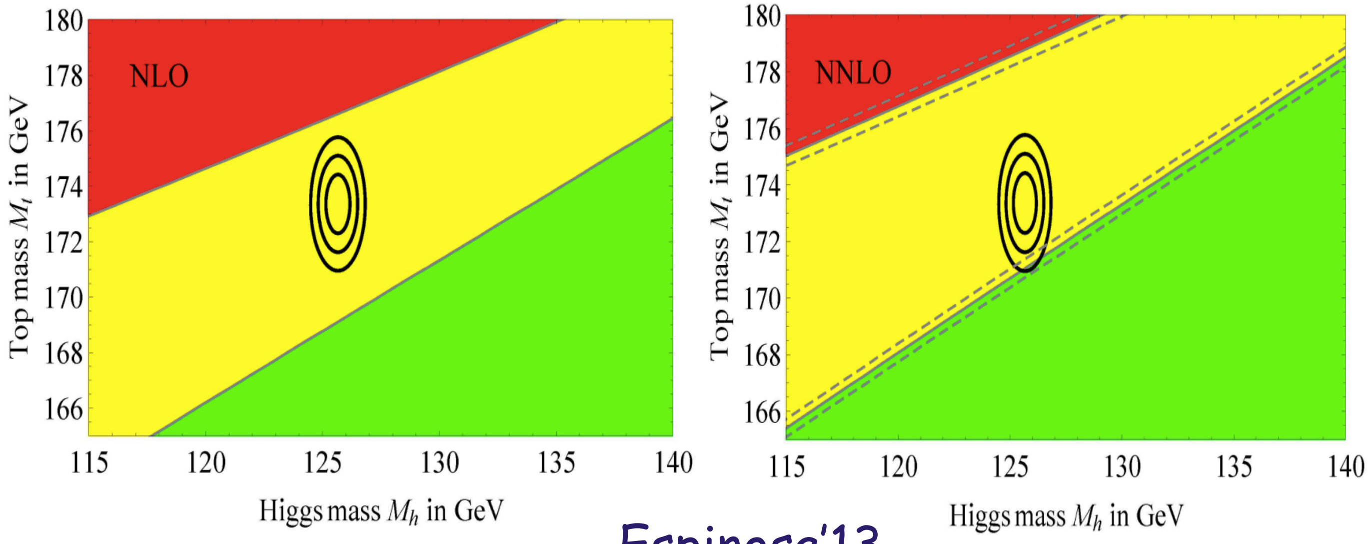

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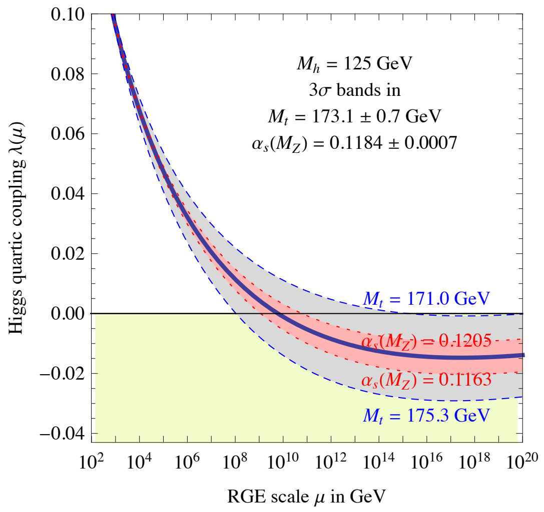
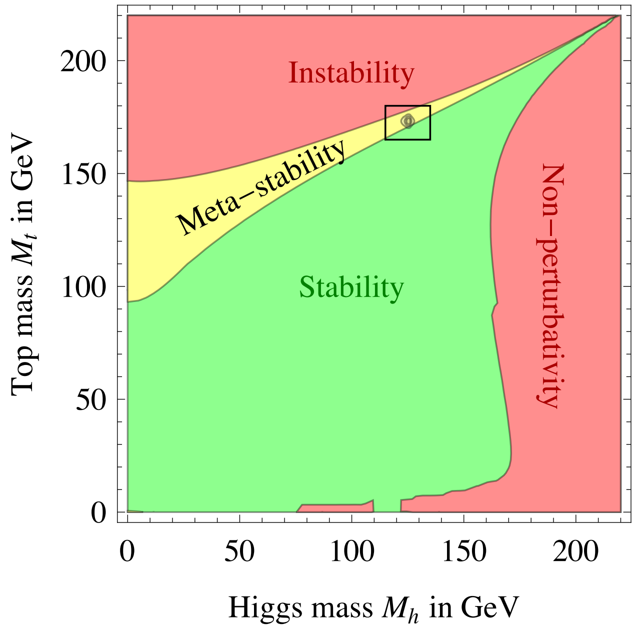
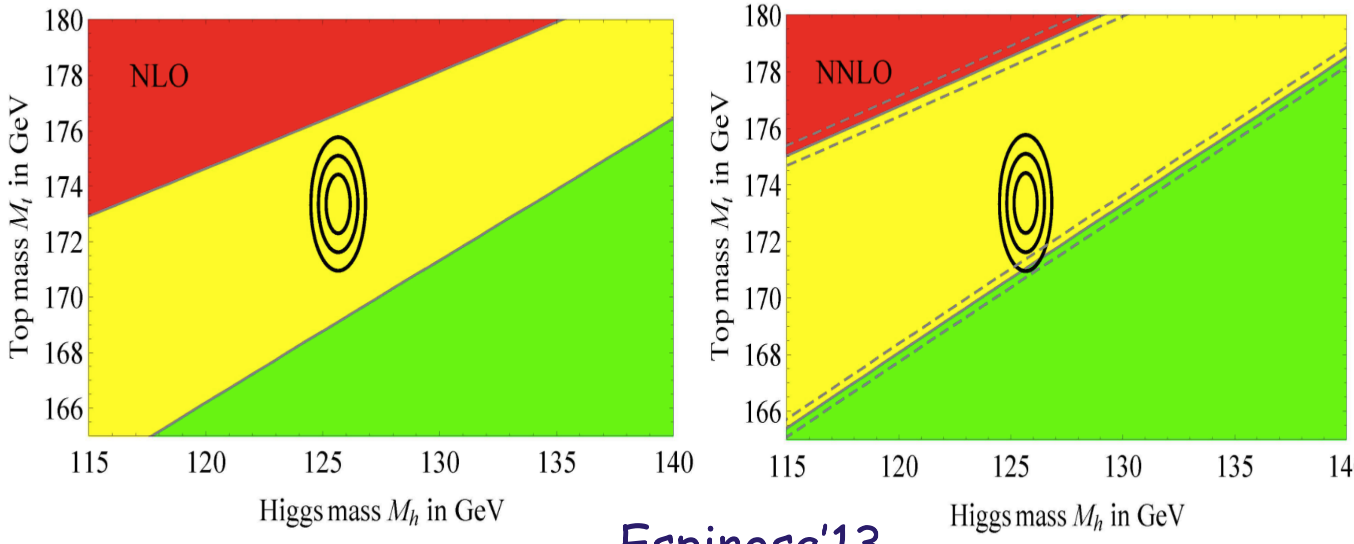
- Extended Higgs sector is another example:

Several Higgs fields with several Higgs-like couplings push the smallest coupling up (might have also several minima)







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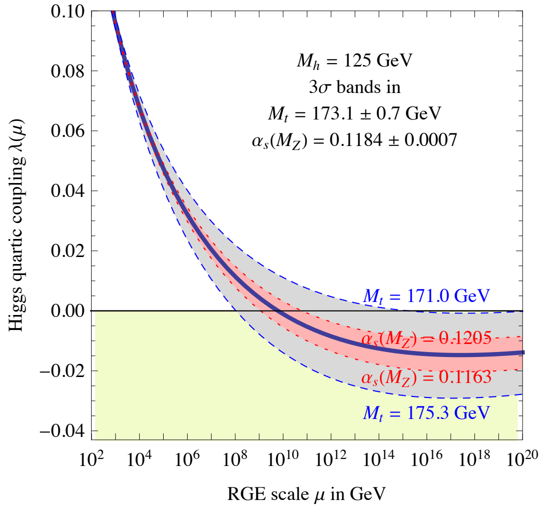

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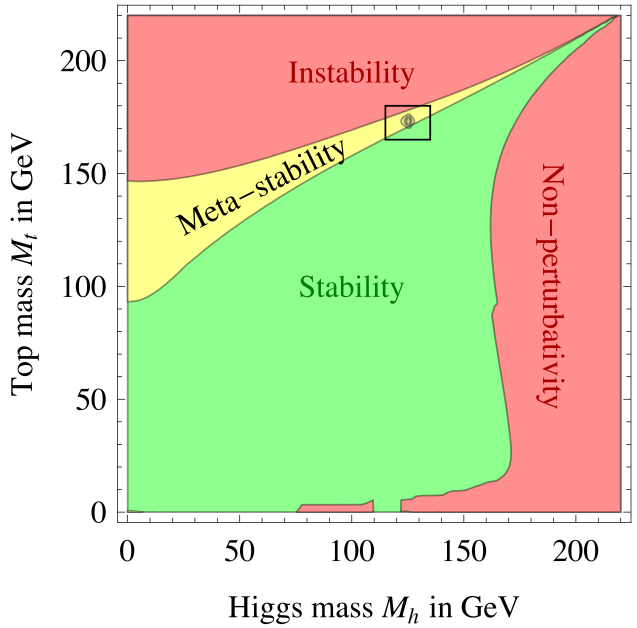


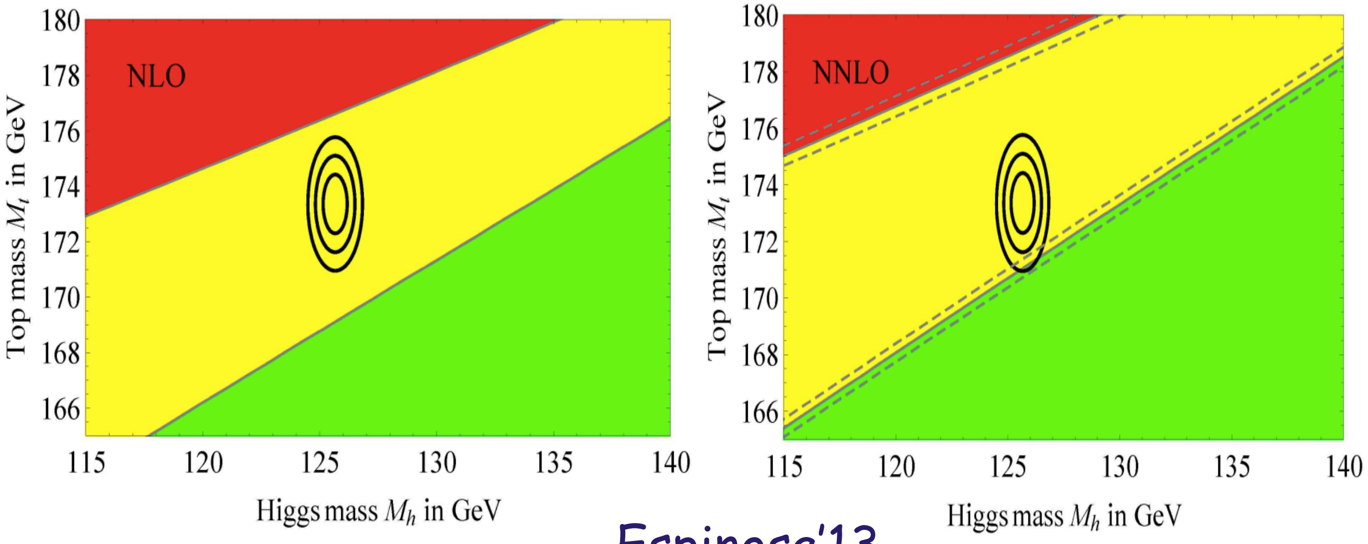
The way out might be the new physics at higher scale:

- SUSY is one example: $V_{SUSY} = |F|^2 + |D|^2 \geq 0$
- Extended Higgs sector is another example:

Several Higgs fields with several Higgs-like couplings push the smallest coupling up (might have also several minima)

- GUT's provide the third example:

In a unified theory the Higgs coupling might be attracted by the gauge coupling and stabilize the potential



Espinosa'13

Is the SM consistent quantum field theory?

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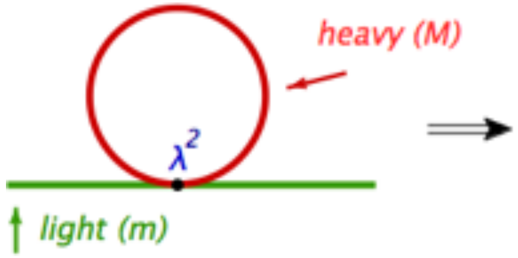
Quantum corrections to the Higgs potential due to New physics



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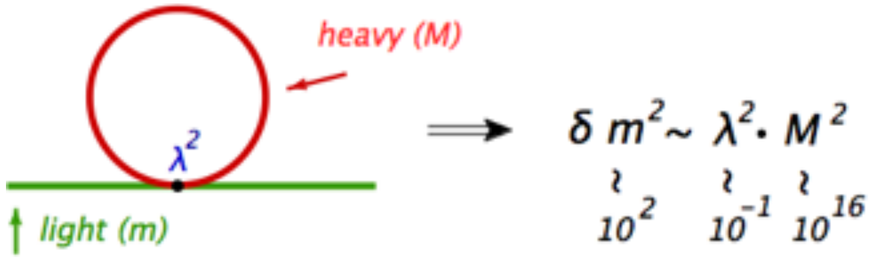

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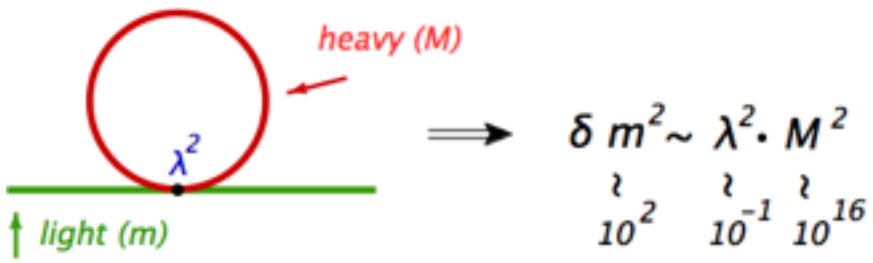

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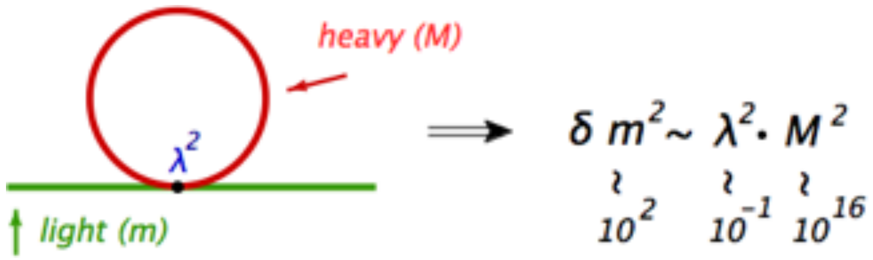

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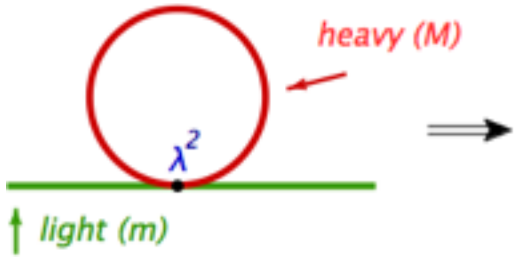

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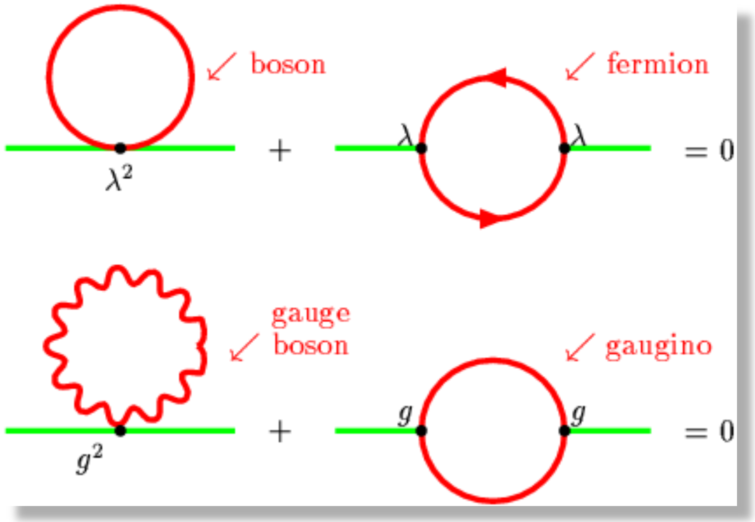

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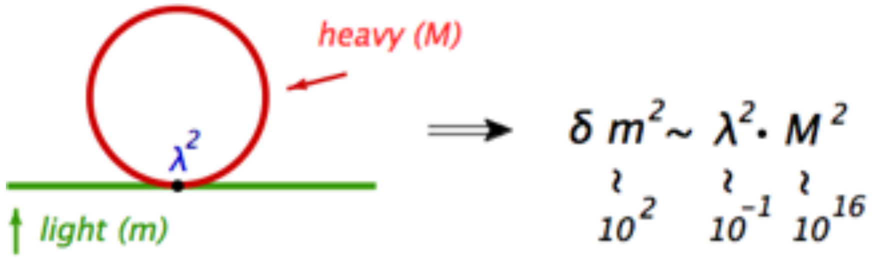

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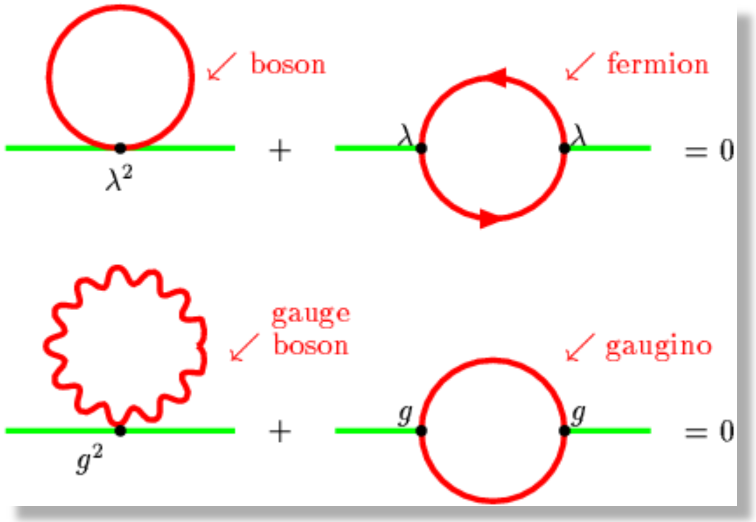

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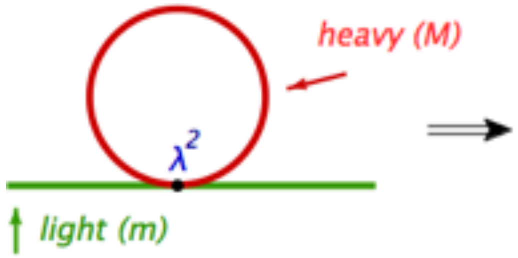

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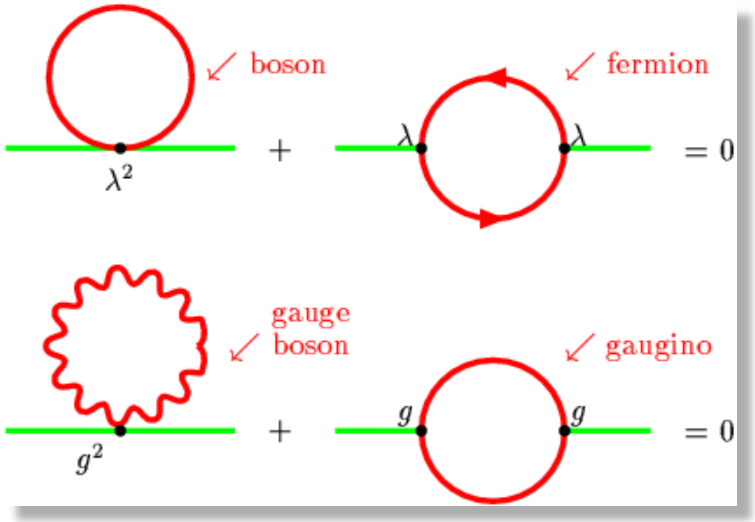

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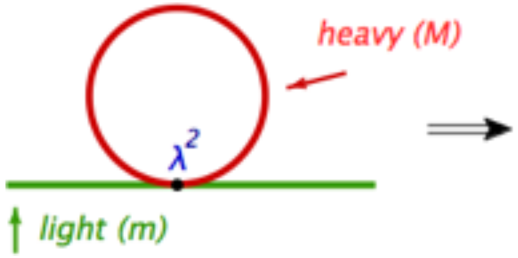

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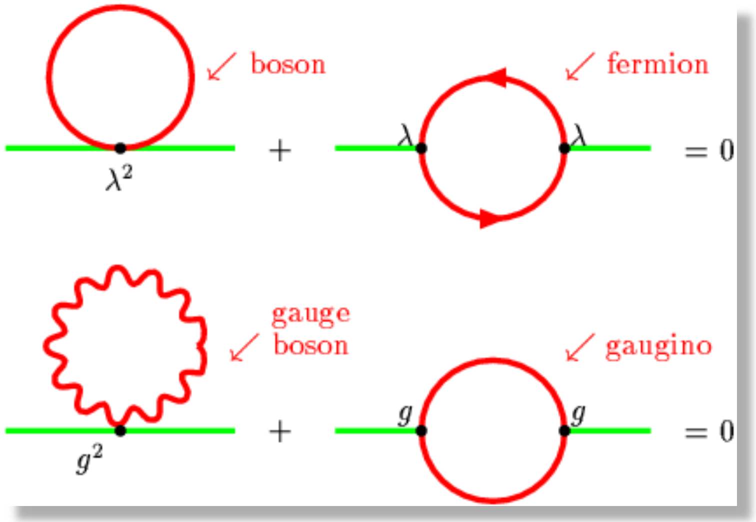

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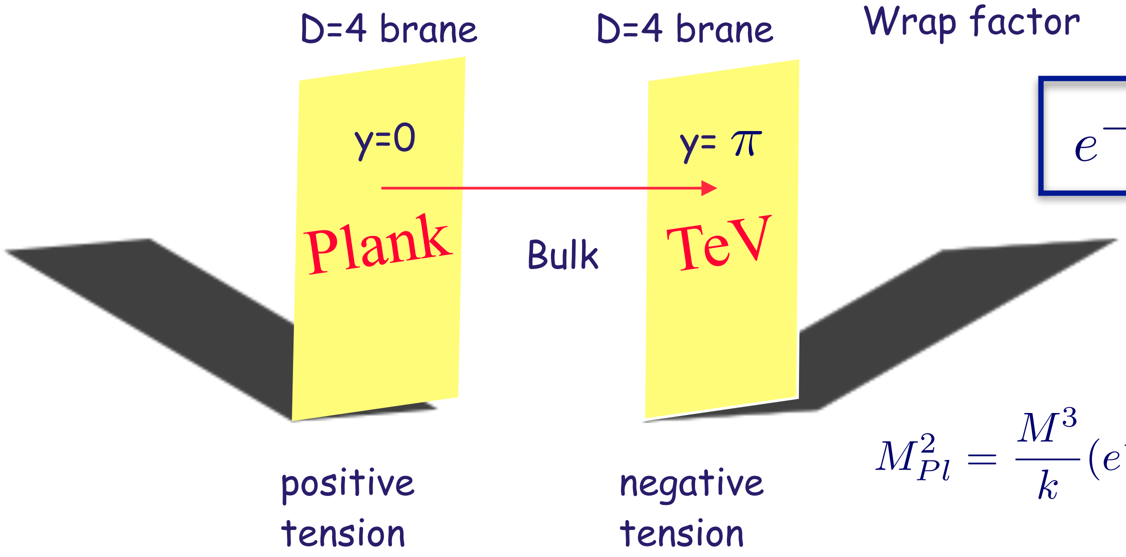


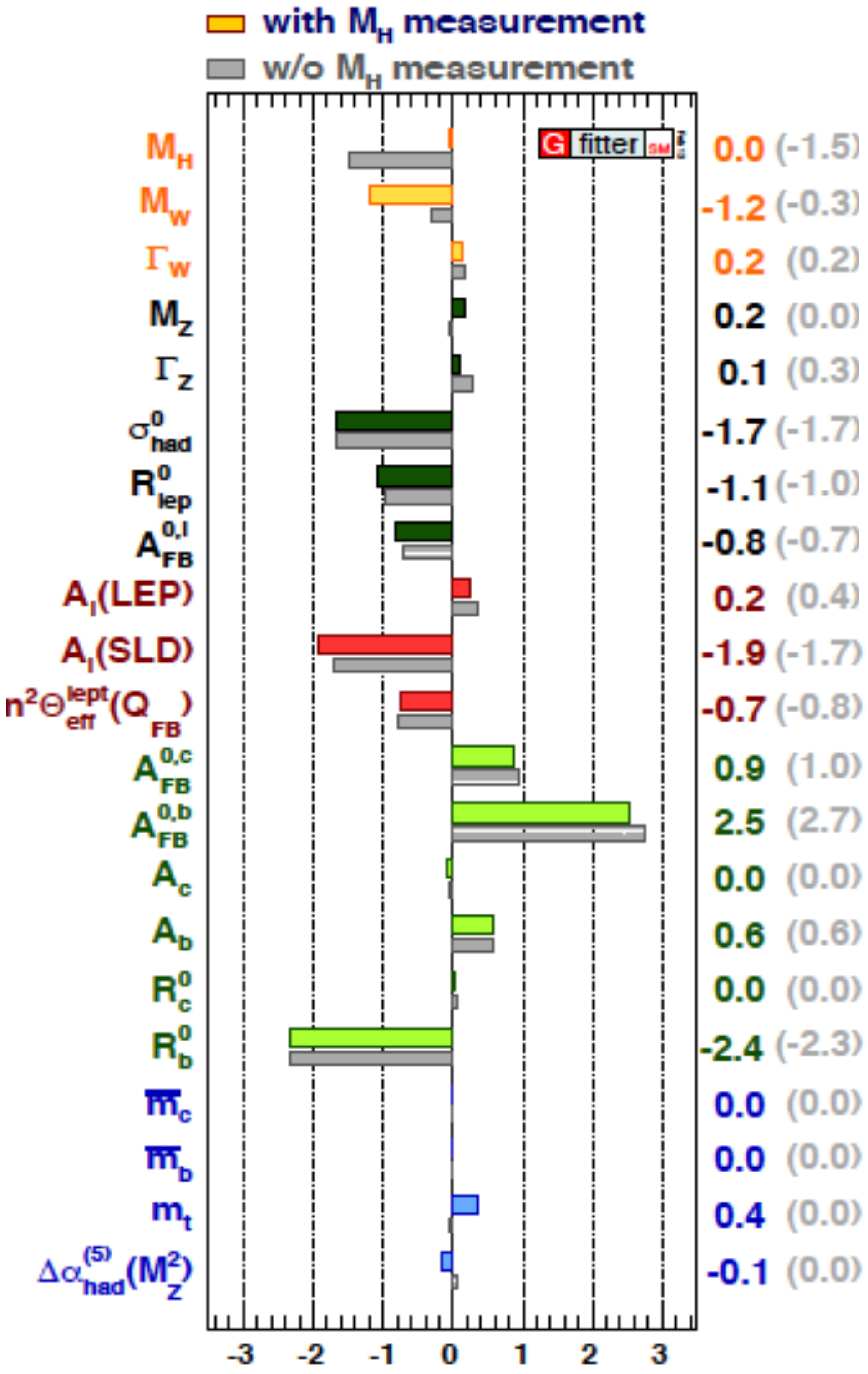
Wrap factor

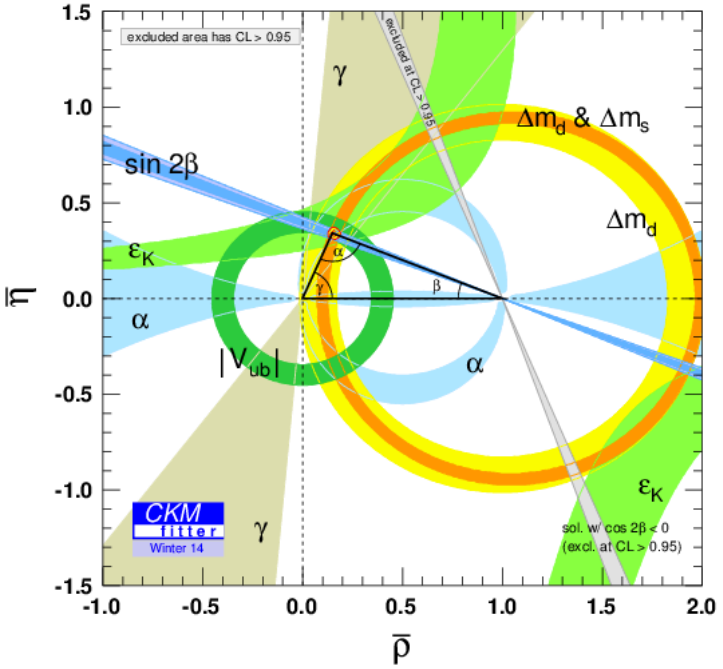
$$\boxed{e^{-2\sigma(\pi R)}}$$

$$M_{Pl}^2 = \frac{M^3}{k}(e^{-2\sigma\pi R} - 1)$$

Does the ST describes all experimental data?

- EW observables pool
- Flavour Physics observ





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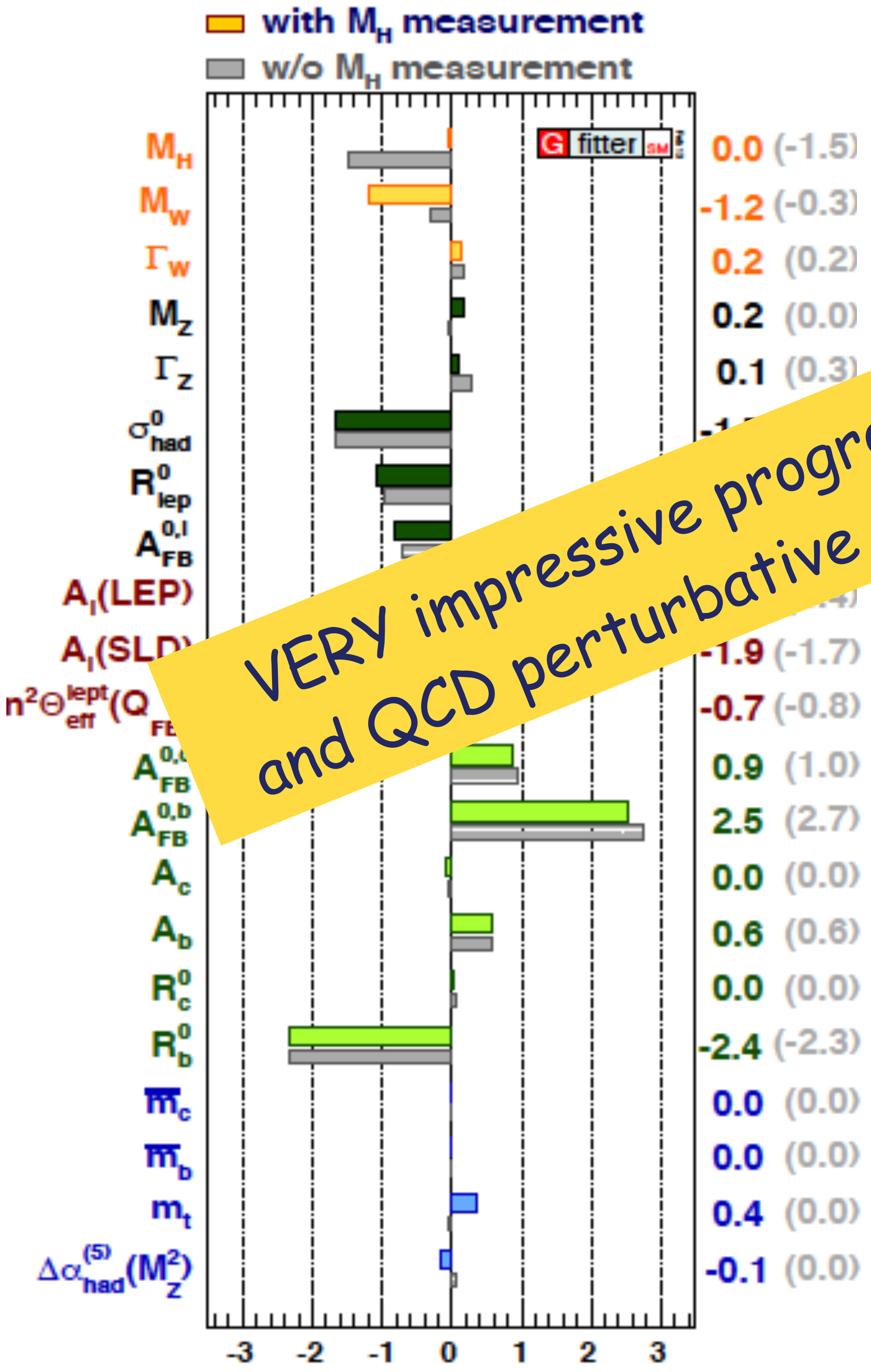

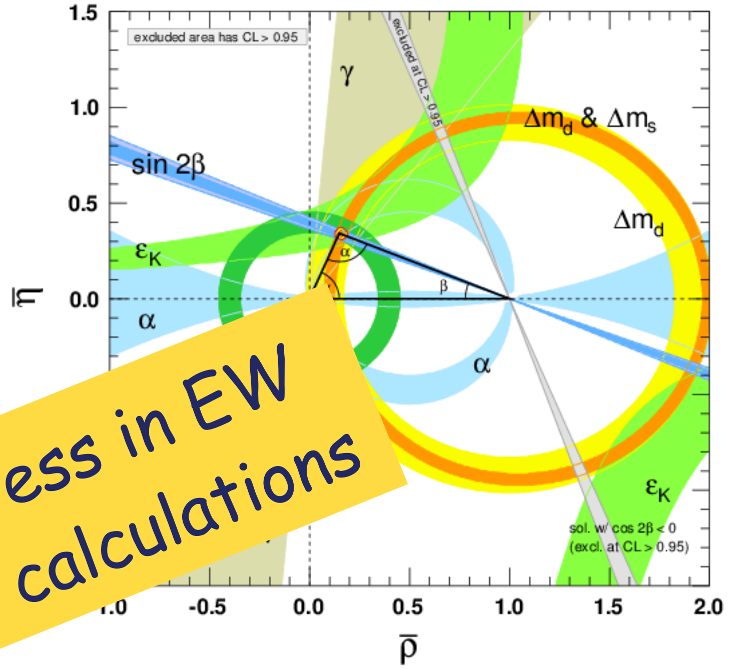

VERY impressive progress in EW and QCD perturbative calculations

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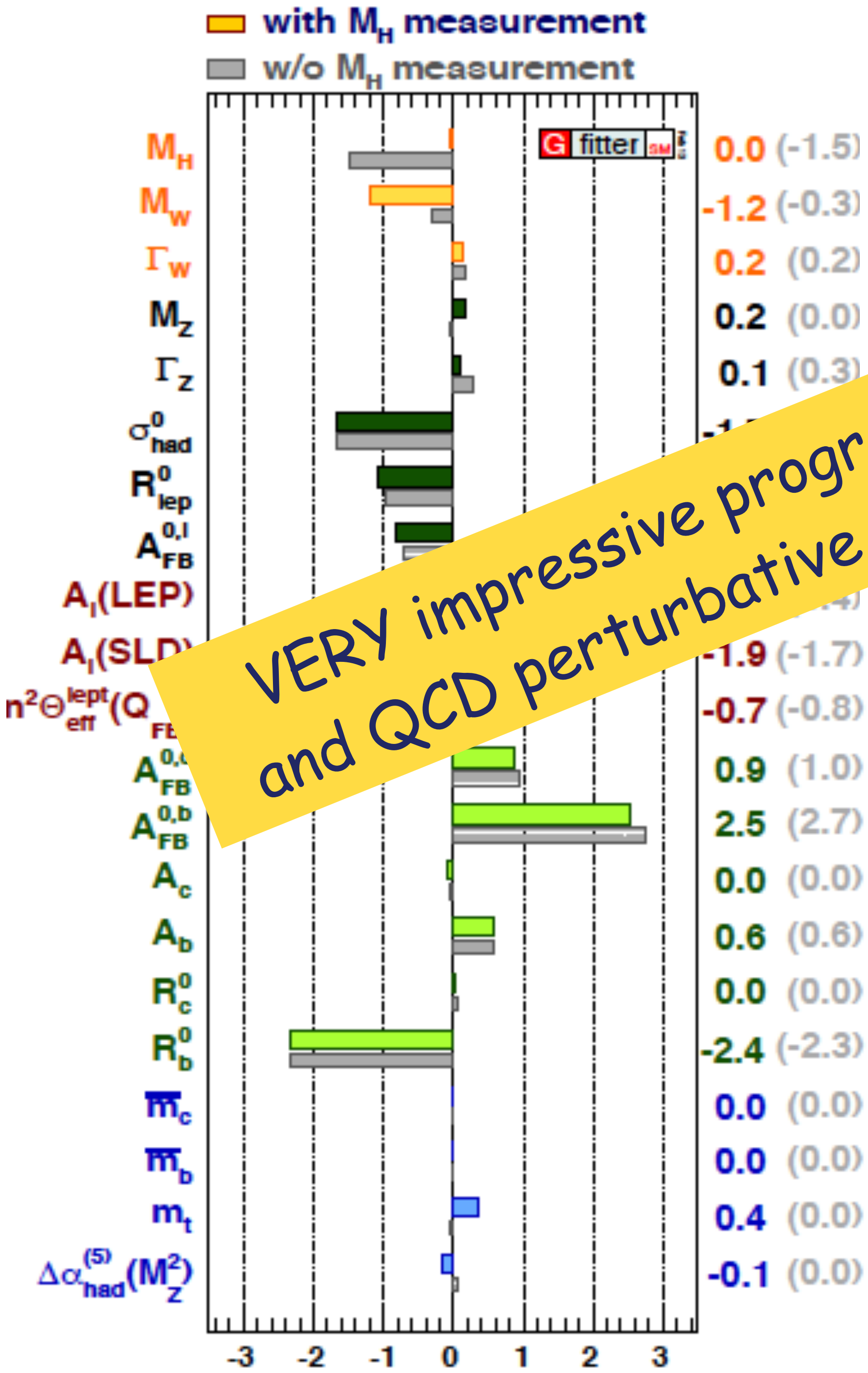

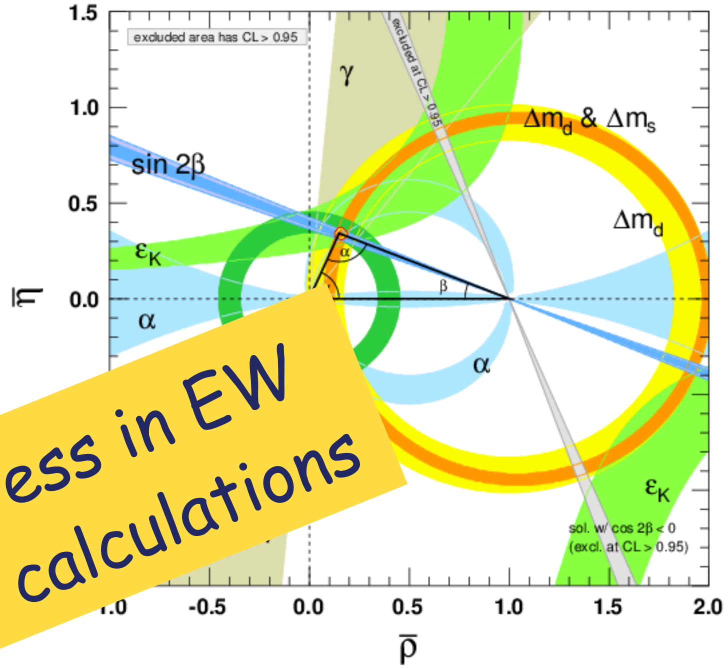

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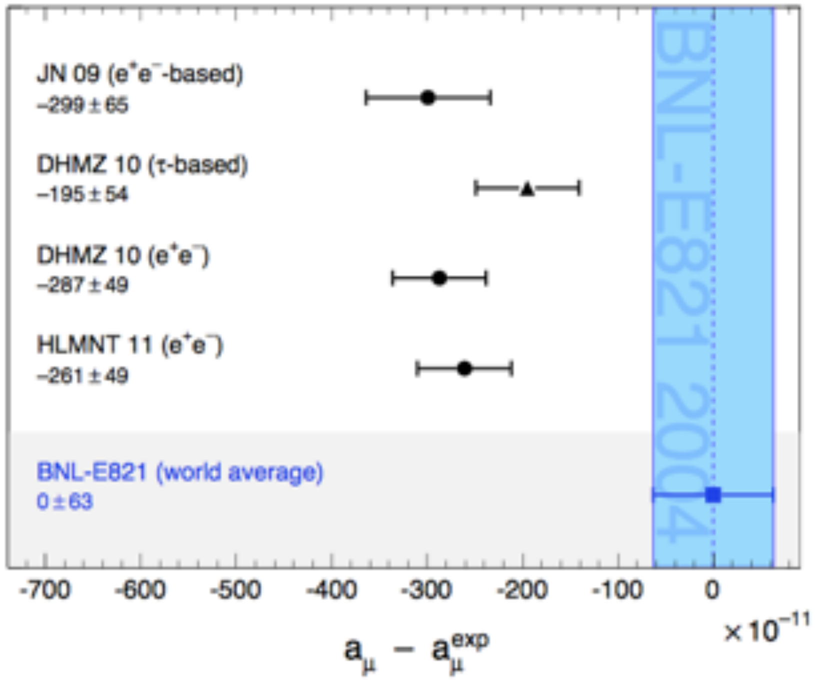

- Forward-backward asymmetries in LEP data - ignored problem
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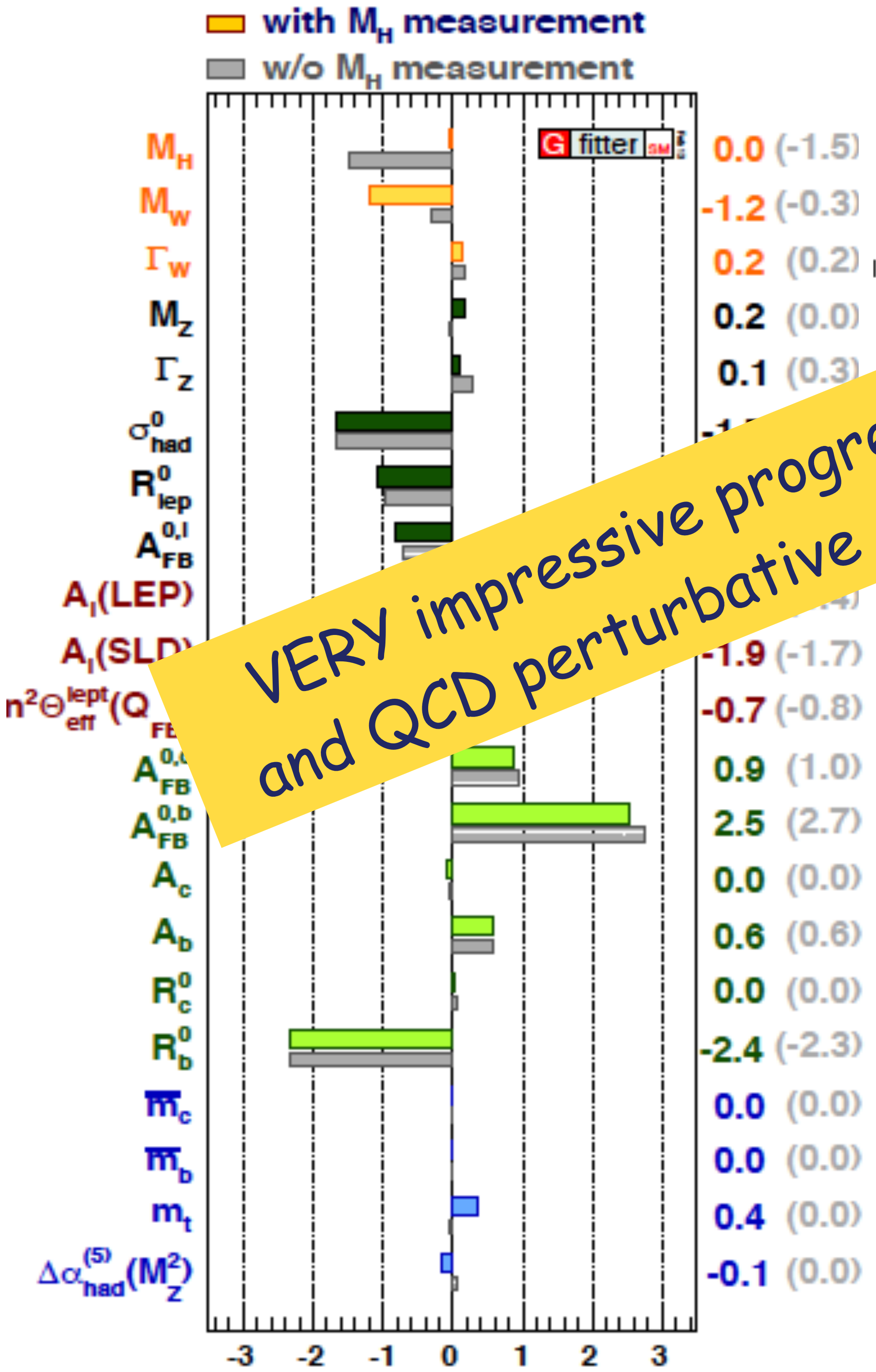

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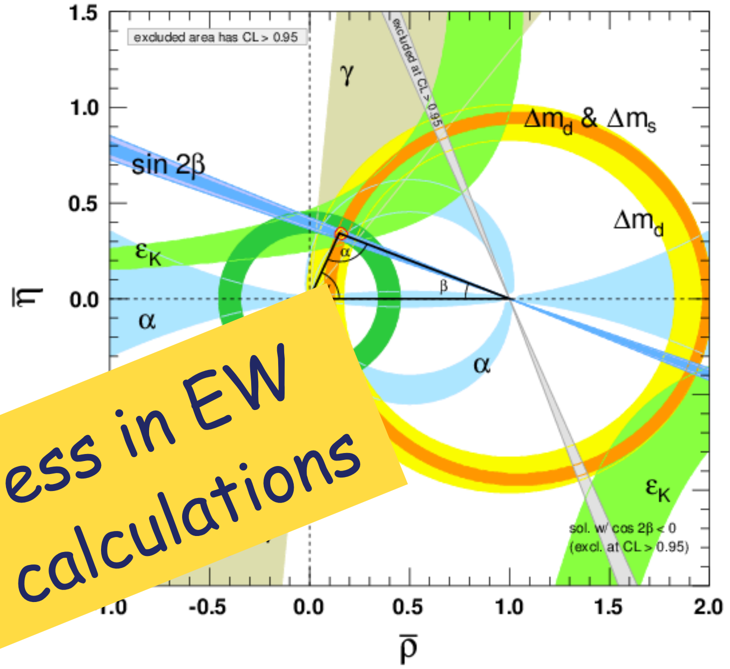

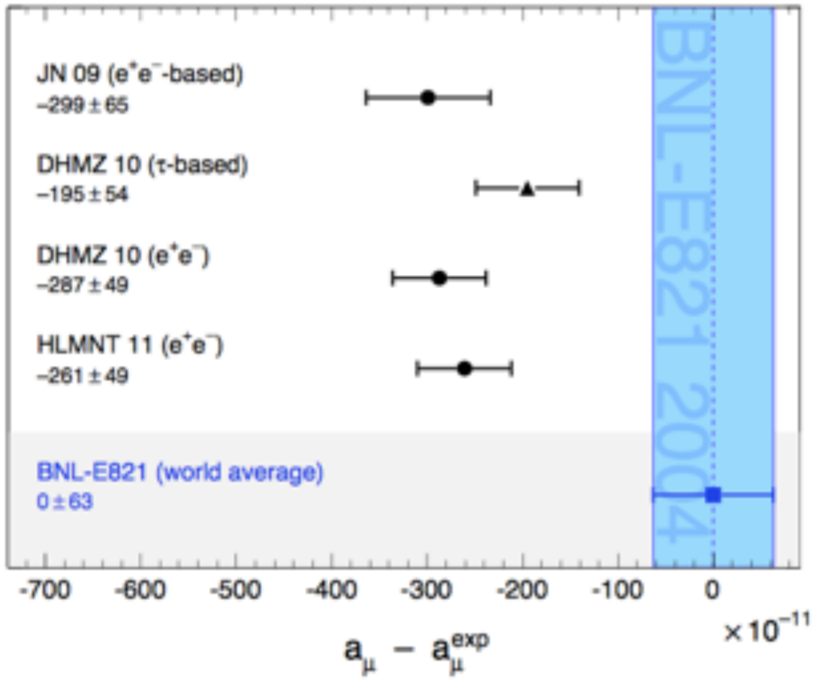

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- strong CP problem: axion field ?
- rare decays: fine so far
- spin crisis in QCD: parton distributions?
- neutrino masses and mixings: looks OK but still needs to be clarified

The Mass Spectrum and Mixing

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- Mass spectrum?

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

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

$$m_W = g/\sqrt{2} \cdot v$$

$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$

$$m_H = \sqrt{\lambda} \cdot v$$

SM

$$m_\gamma = 0$$

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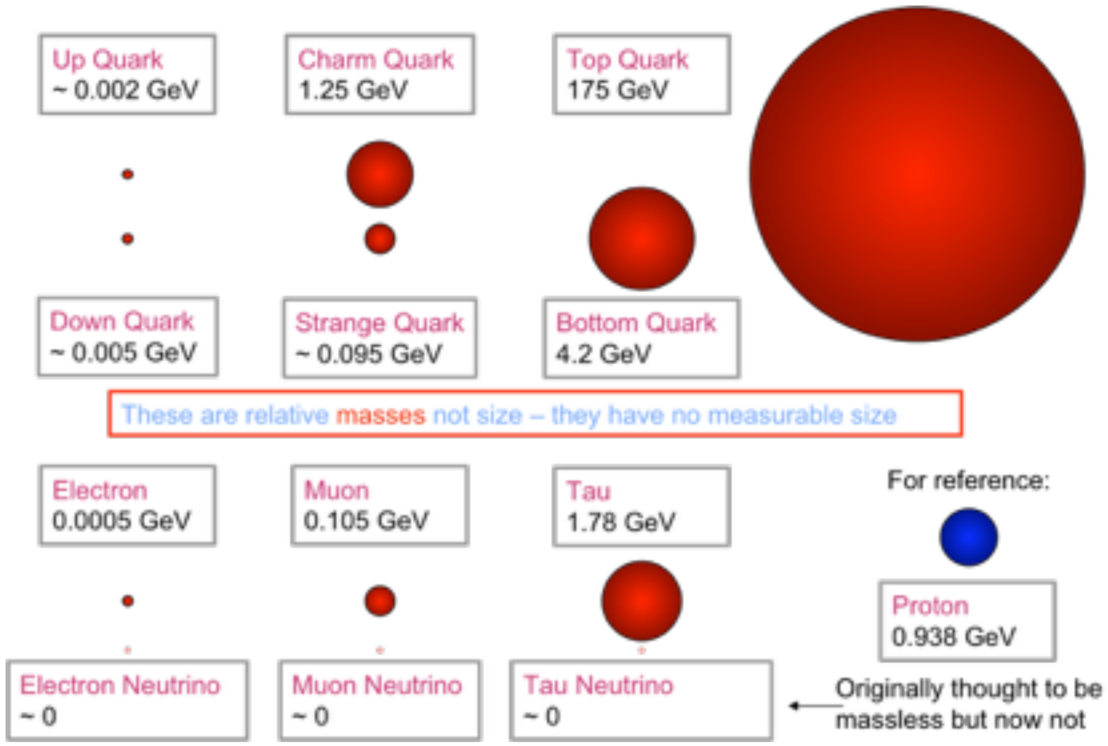

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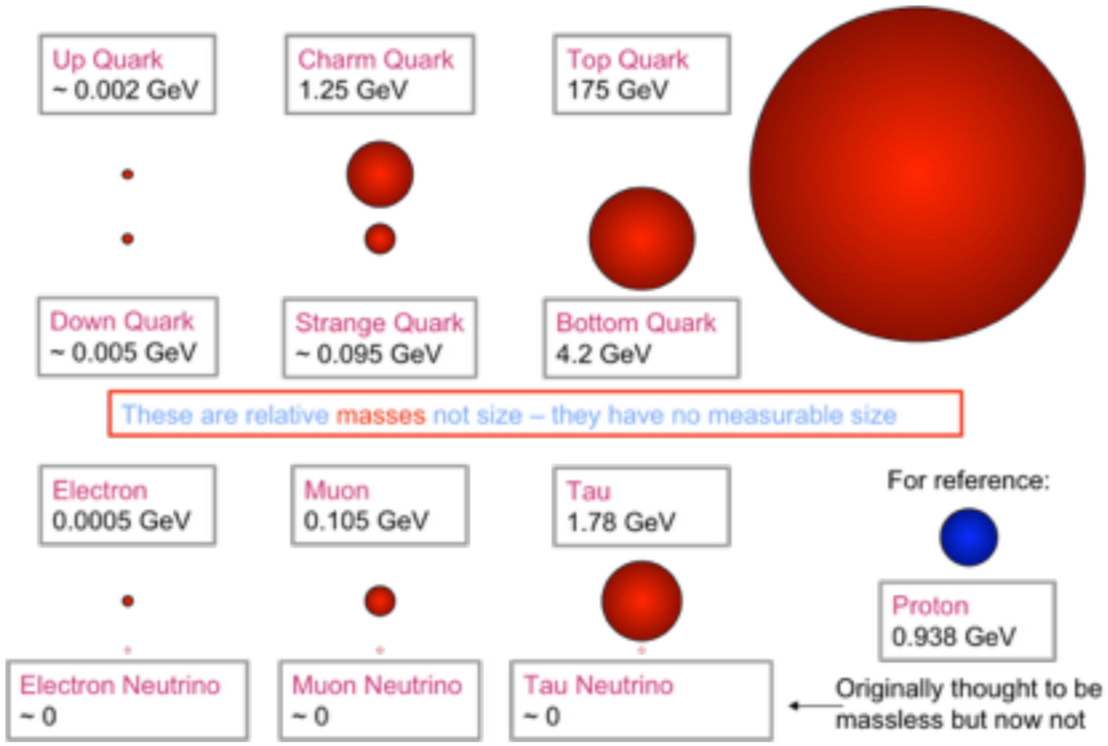

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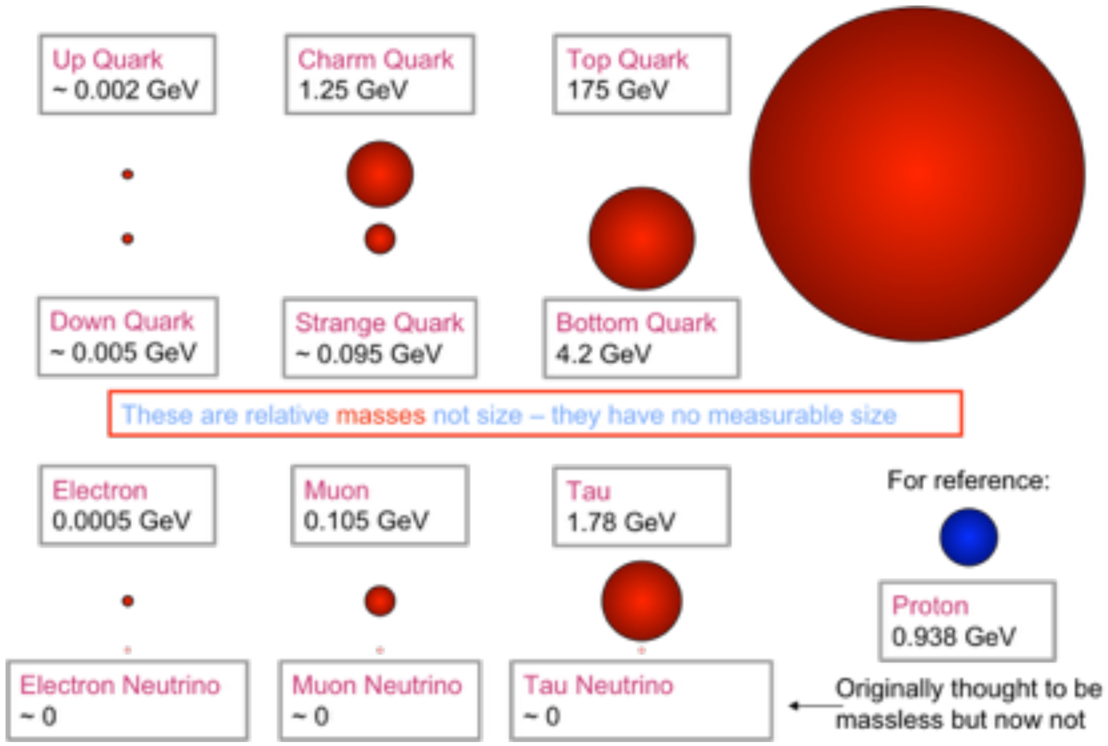

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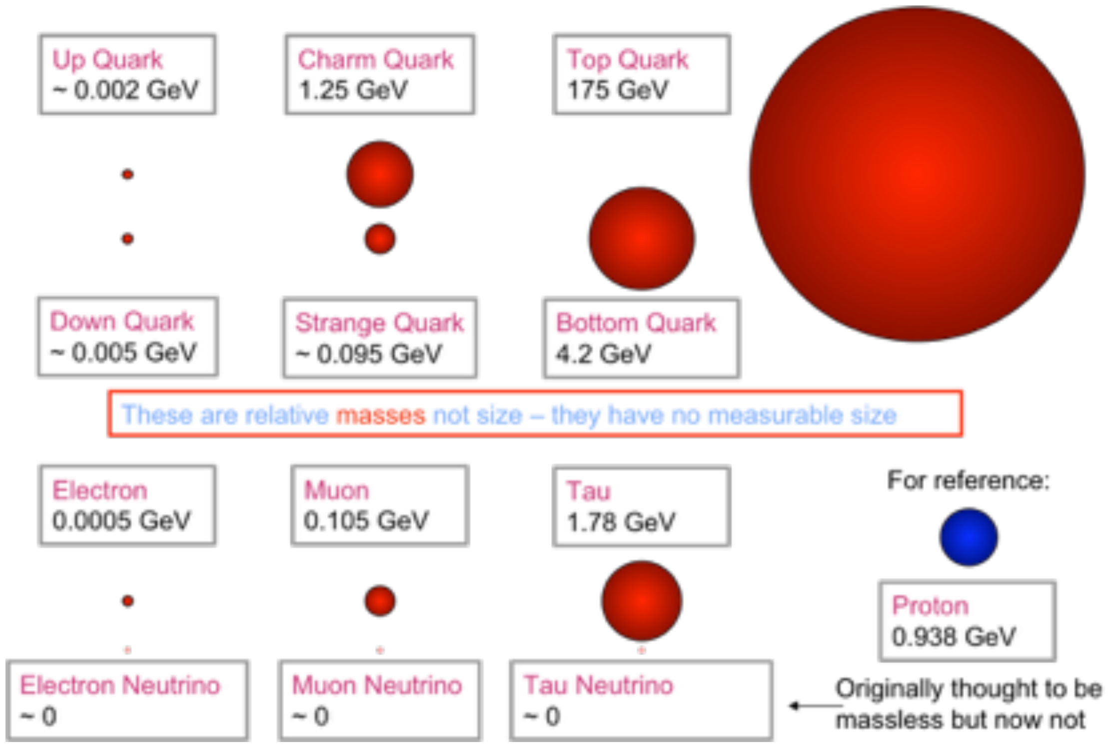

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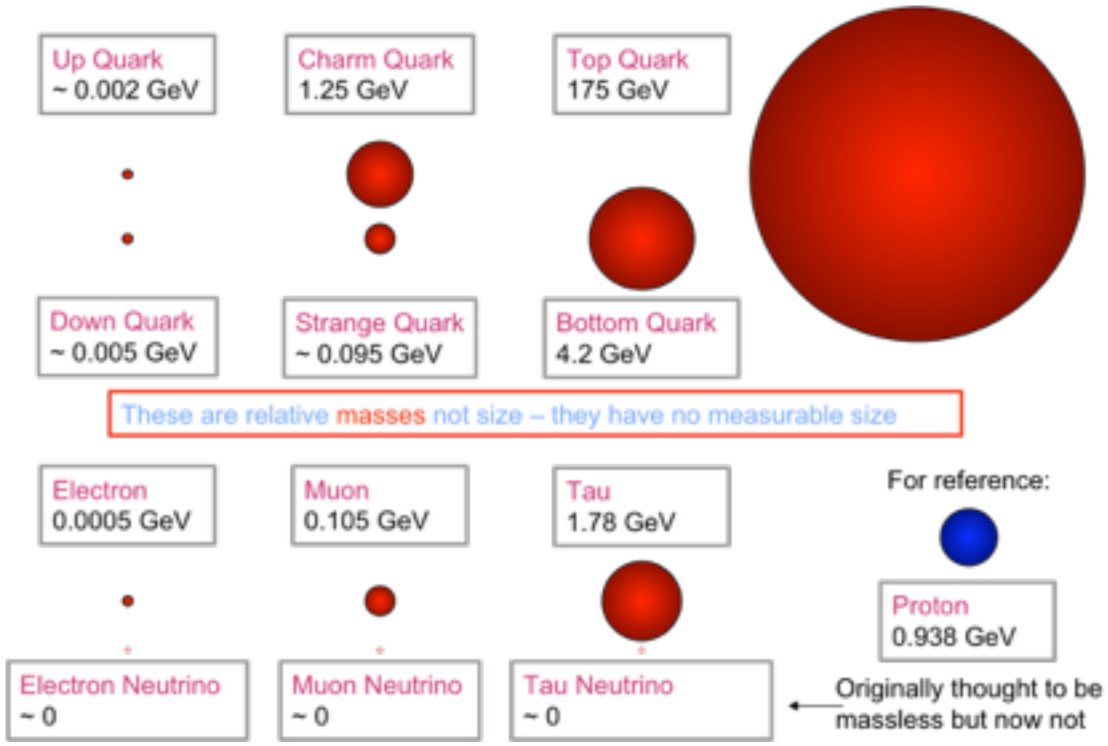

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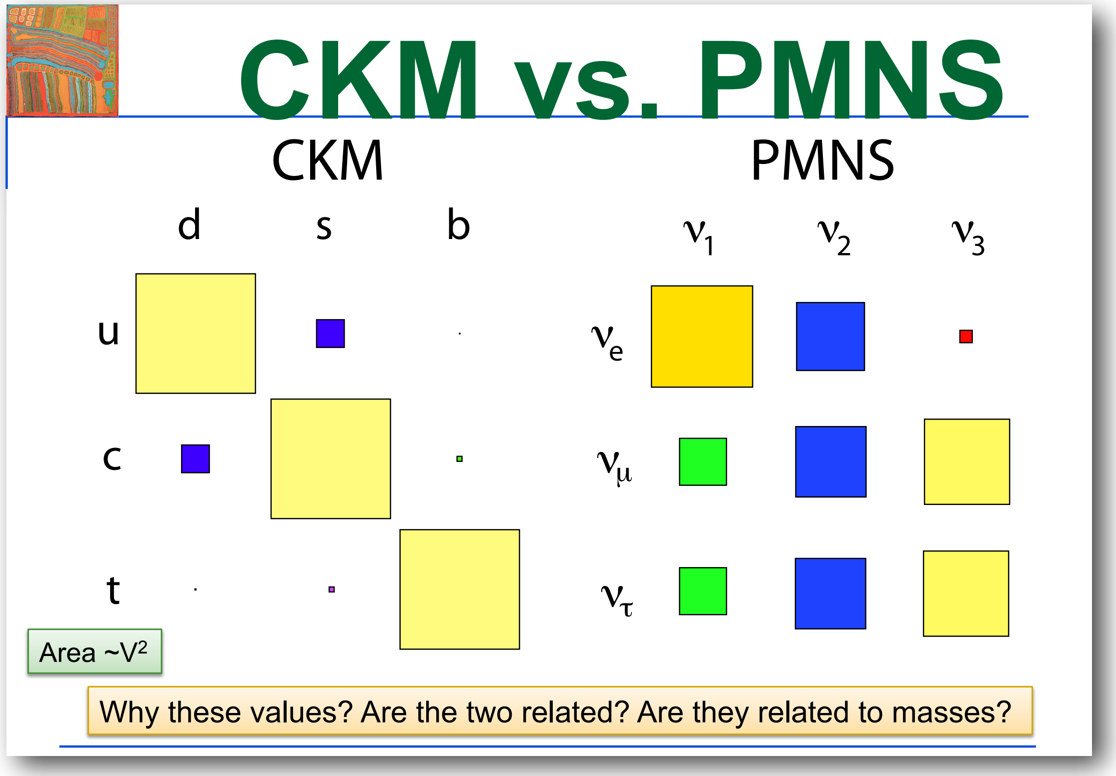

CKM vs. PMNS

CKM

$d \quad s \quad b$

$u \quad c \quad t$

PMNS

$\nu_1 \quad \nu_2 \quad \nu_3$

$\nu_e \quad \nu_\mu \quad \nu_\tau$

Area ~V²

Why these values? Are the two related? Are they related to masses?

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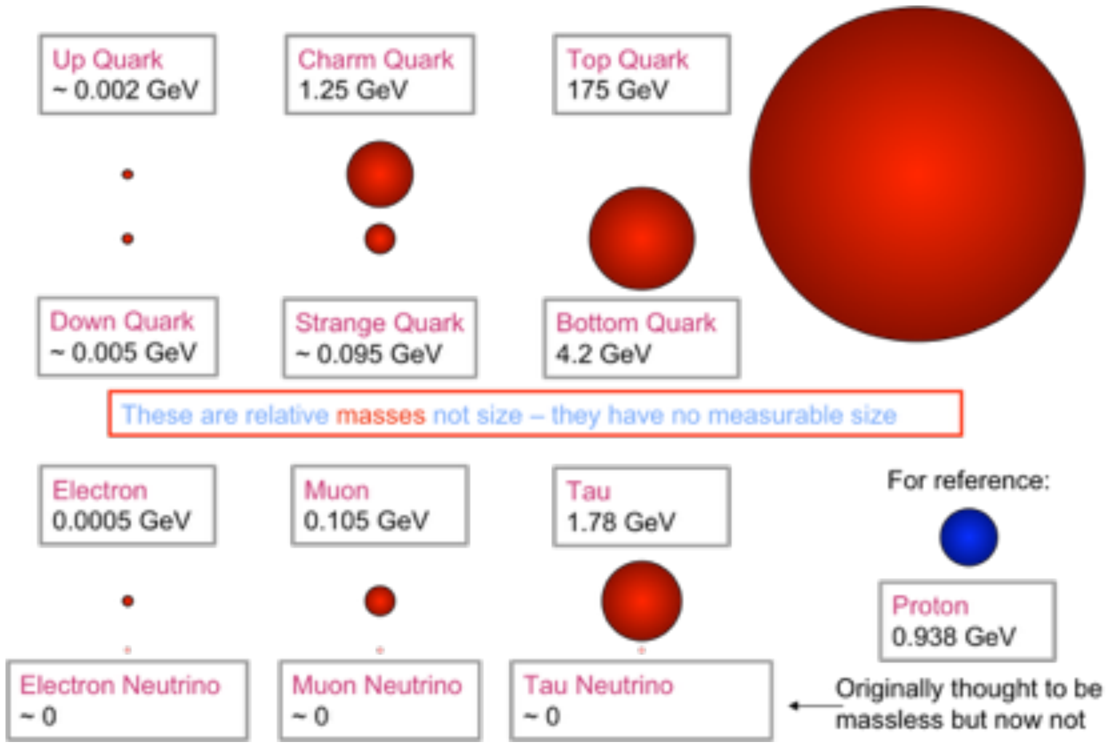

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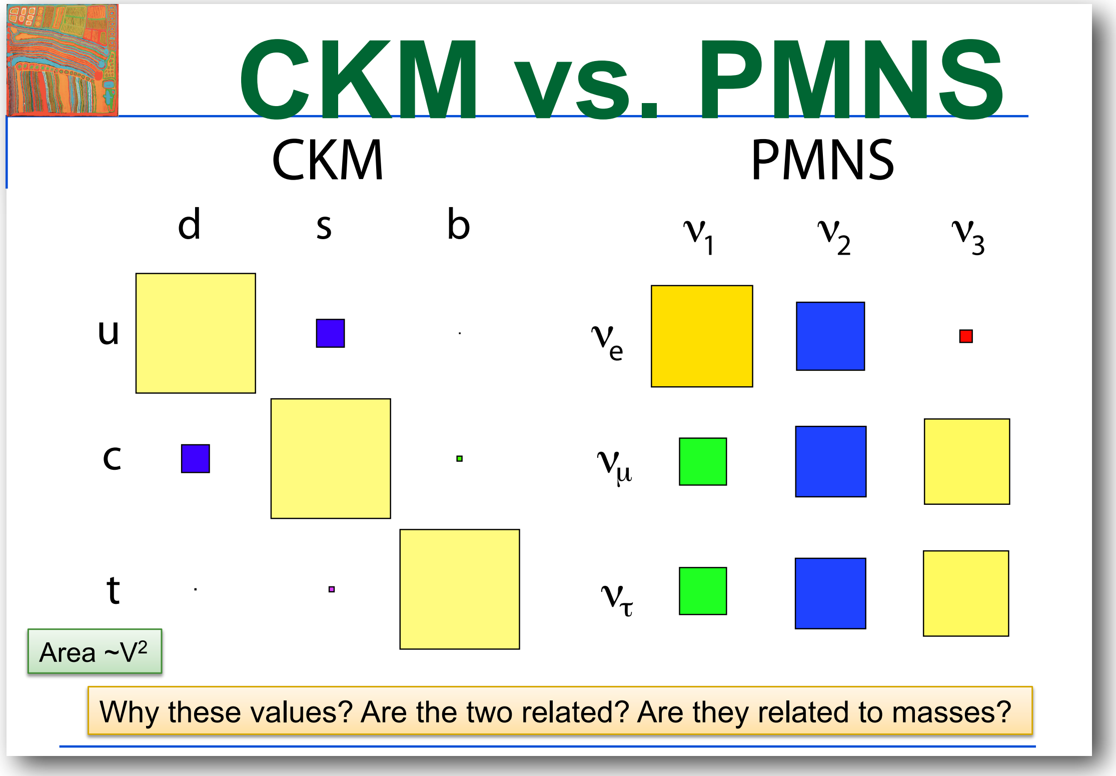

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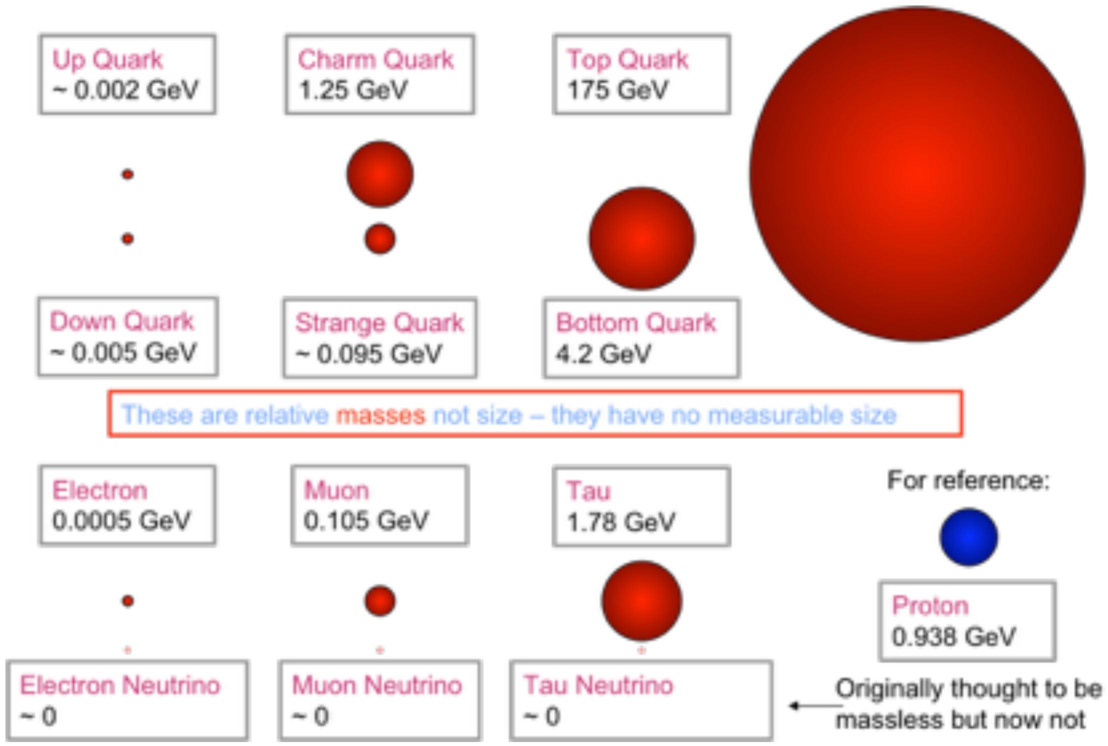

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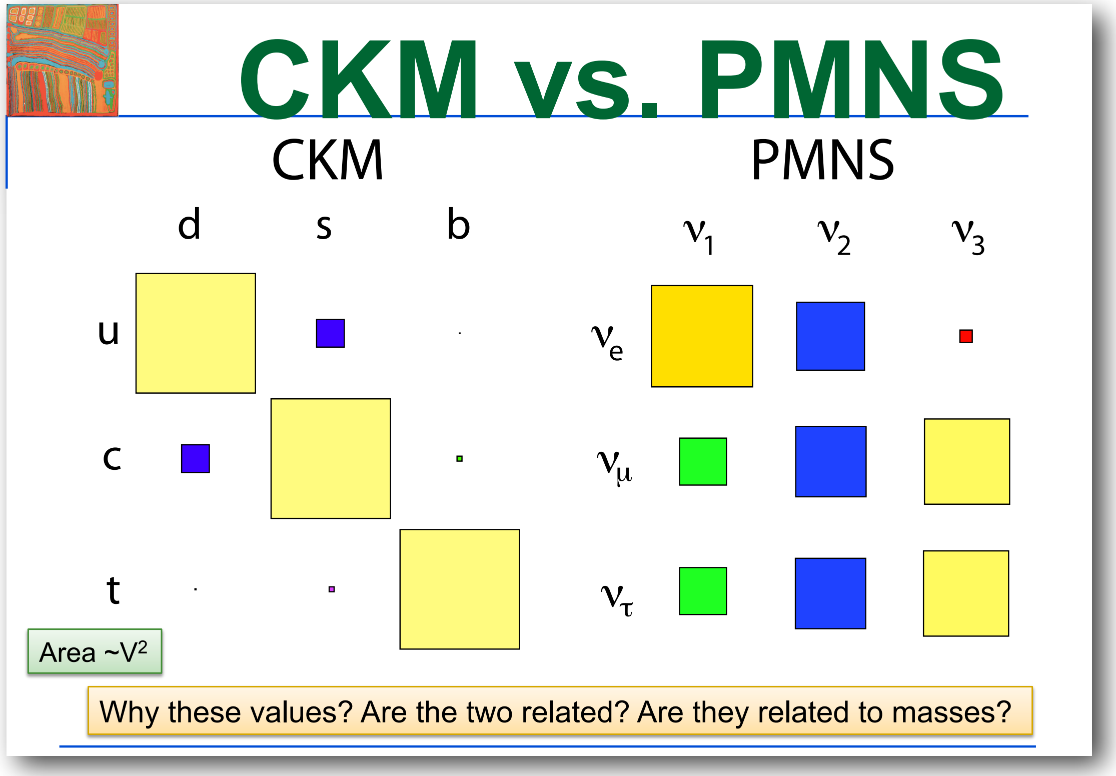

CKM vs. PMNS

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

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Neutrino Sector

Neutrino masses

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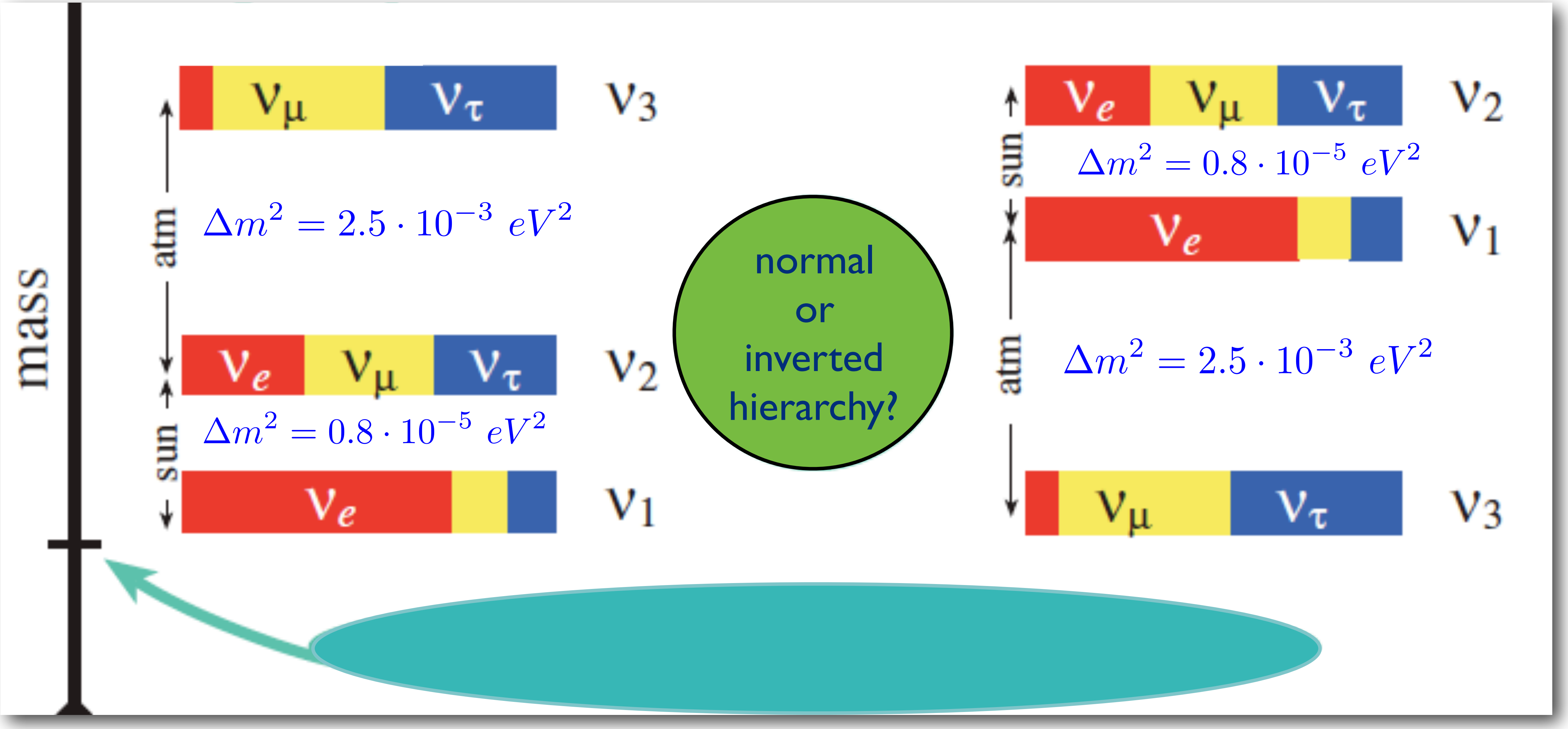

Neutrino Sector

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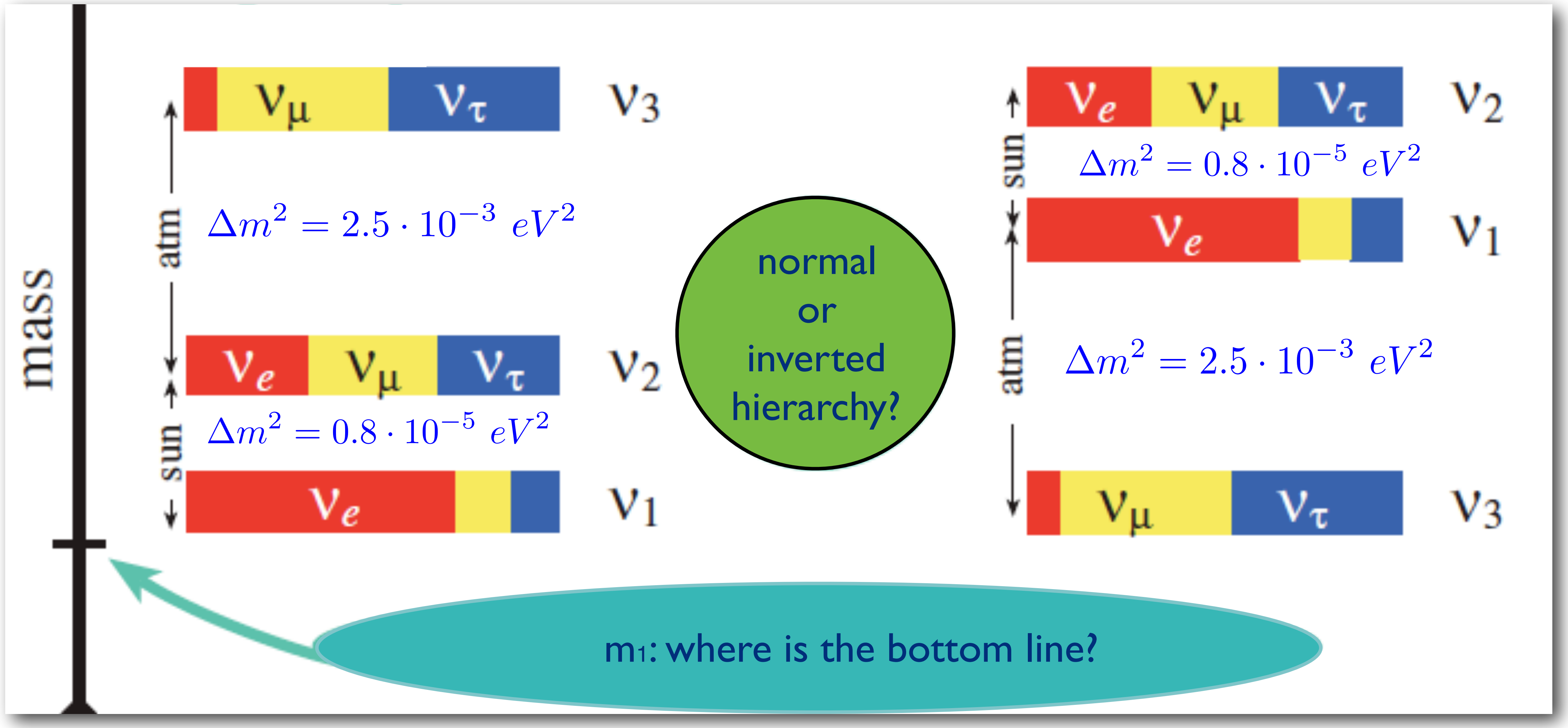

normal or inverted hierarchy?

m1: where is the bottom line?

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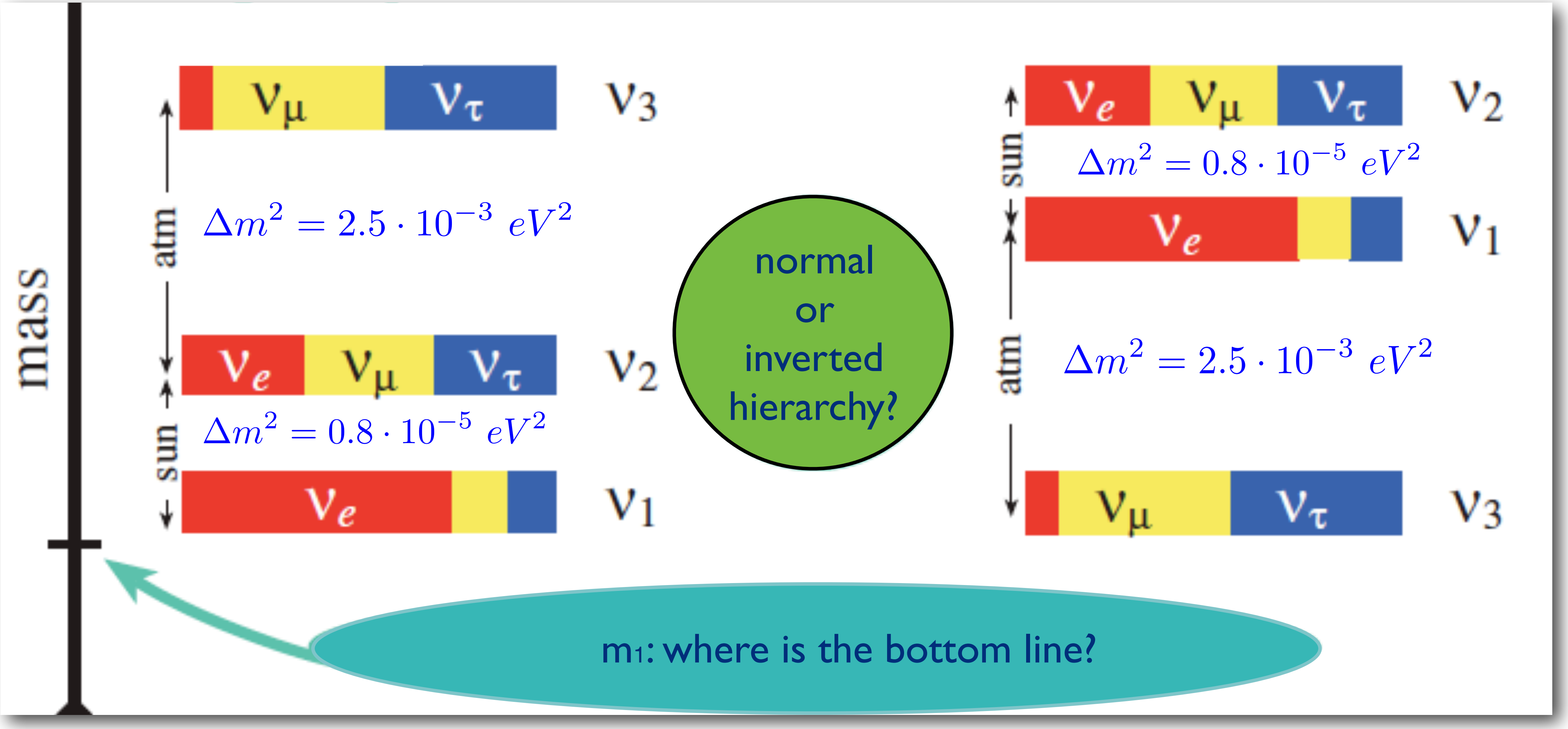


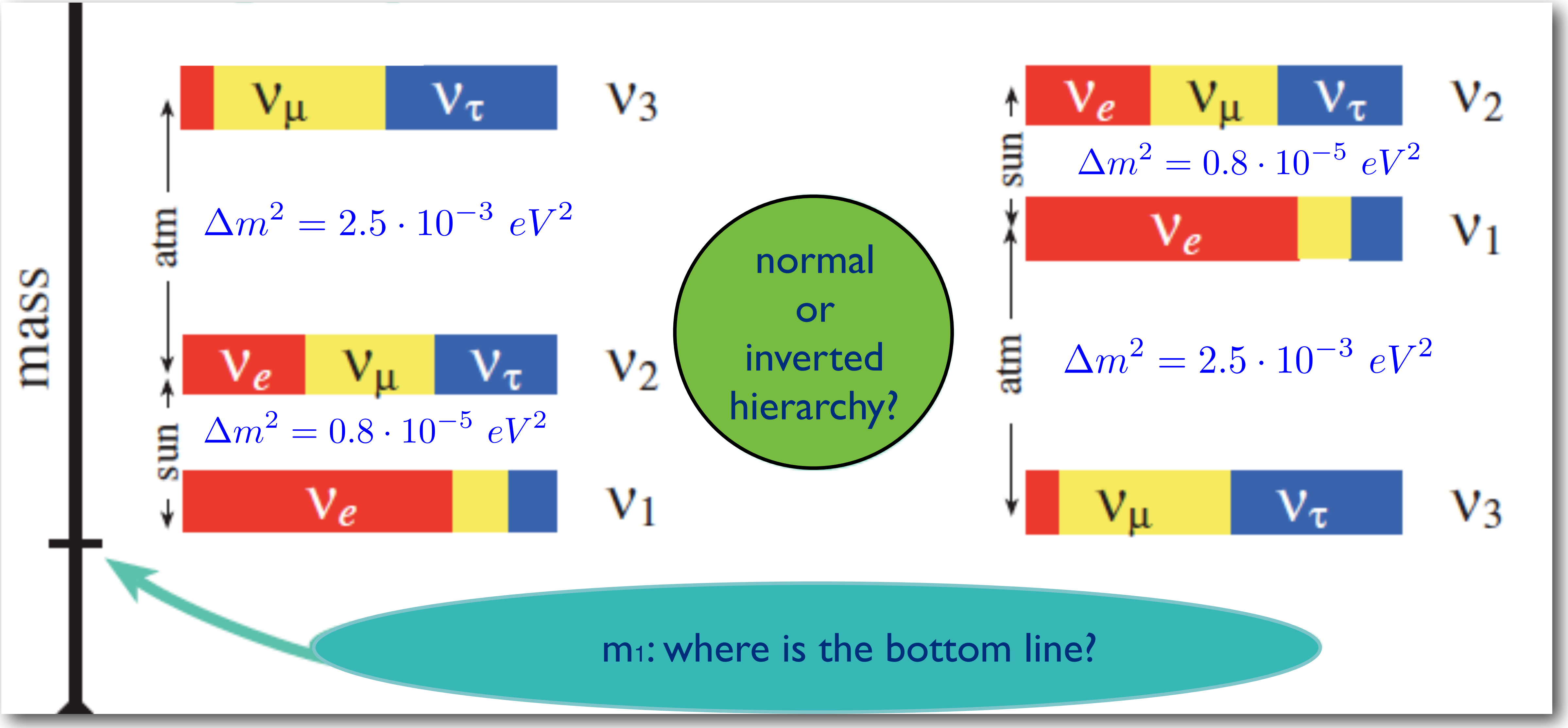
$$\sum m_\nu < 0.23\ eV$$

cosmology: the CMB spectrum

Planck

Neutrino Sector

Neutrino masses



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β-decay

Troitsk-Mainz

Neutrino Sector

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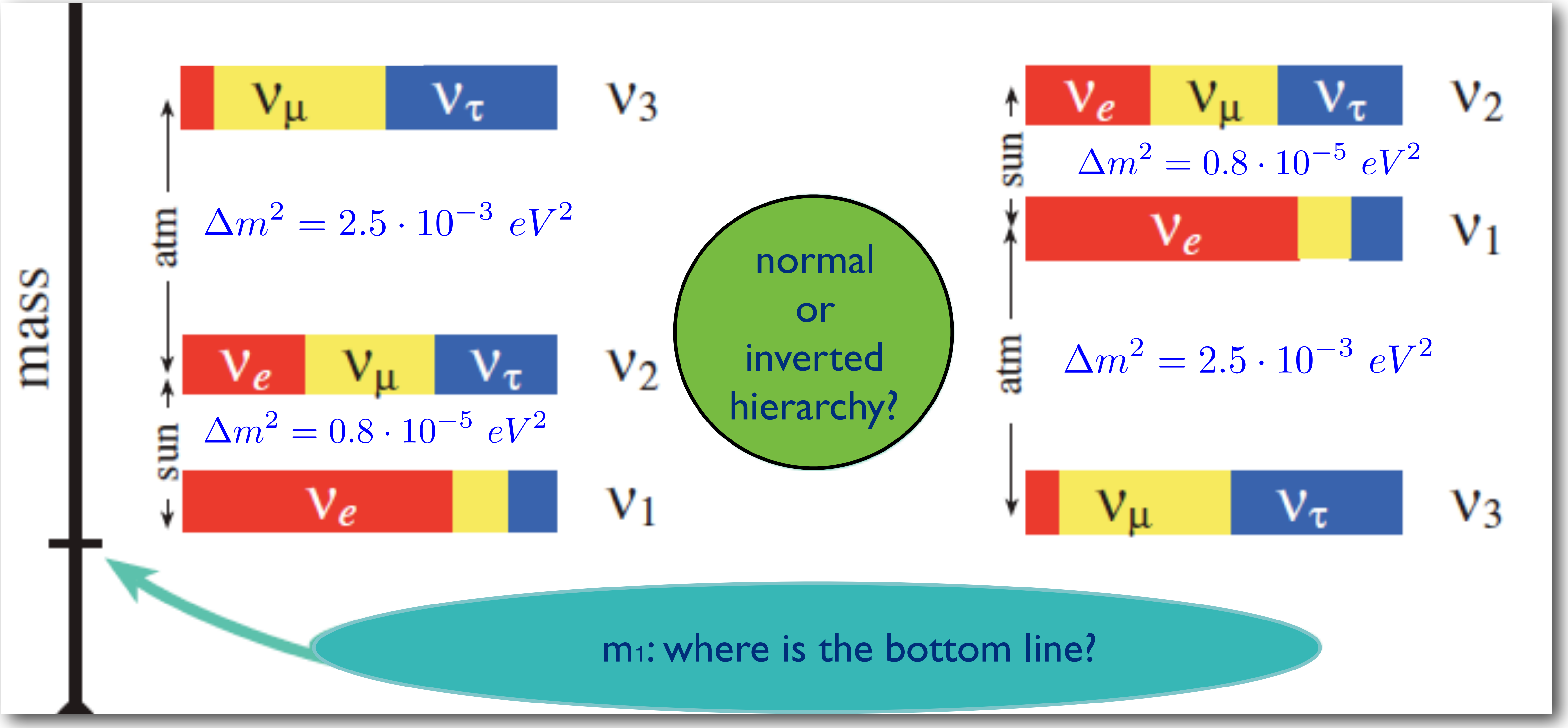

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β-decay

Troitsk-Mainz

KATRIN

Neutrino Sector

Dirac or Majorana?

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

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$$\nu_D \neq \nu_D^*$$

$$m_{\nu_L} = m_{\nu_R}$$

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$$m_{\nu_L} = m_{\nu_R}$$

?

$$\nu_M = \nu_M^*$$

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

Neutrino Sector

Dirac or Majorana?

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

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?

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0νββ decay

Neutrino Sector

Dirac or Majorana?

$$\nu_D = \left(\begin{array}{c} \nu_L \\ \nu_R \end{array} \right) \qquad \nu_{M_1} = \left(\begin{array}{c} \xi_1 \\ \xi_1^* \end{array} \right) , \quad \nu_{M_2} = \left(\begin{array}{c} \xi_2 \\ \xi_2^* \end{array} \right)$$

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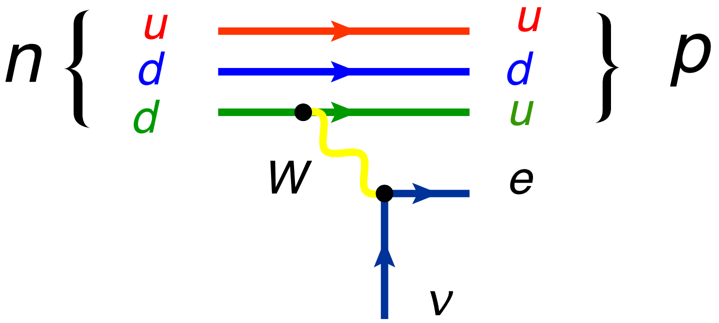
0νββ decay



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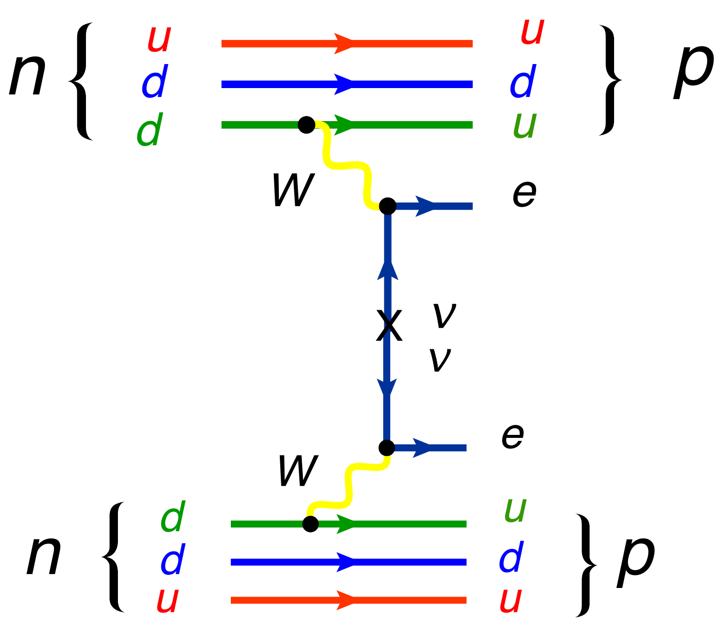

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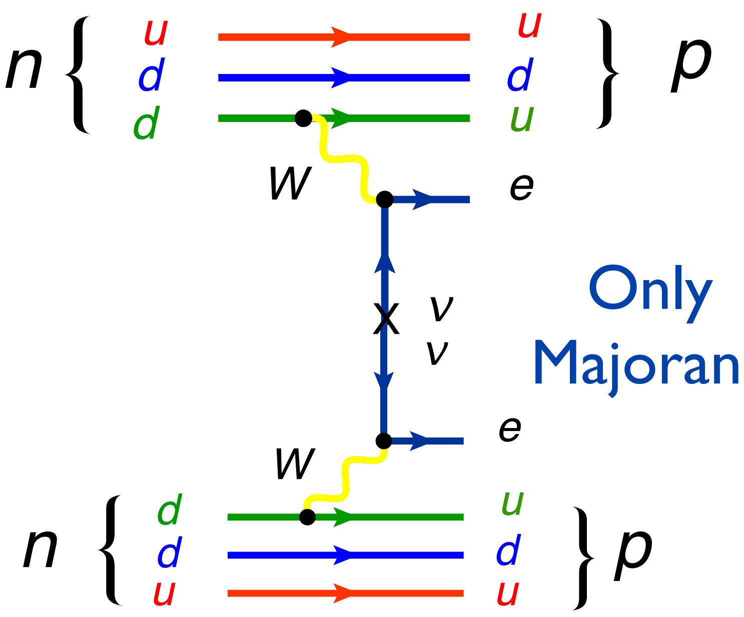

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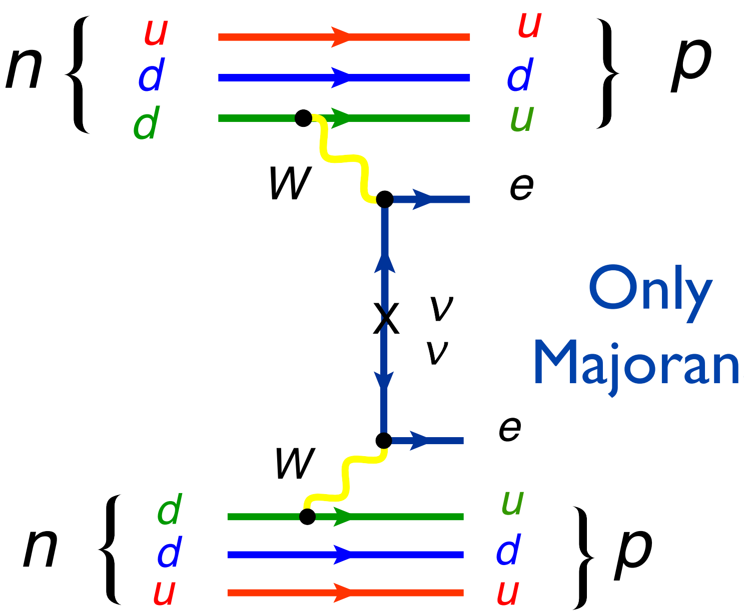
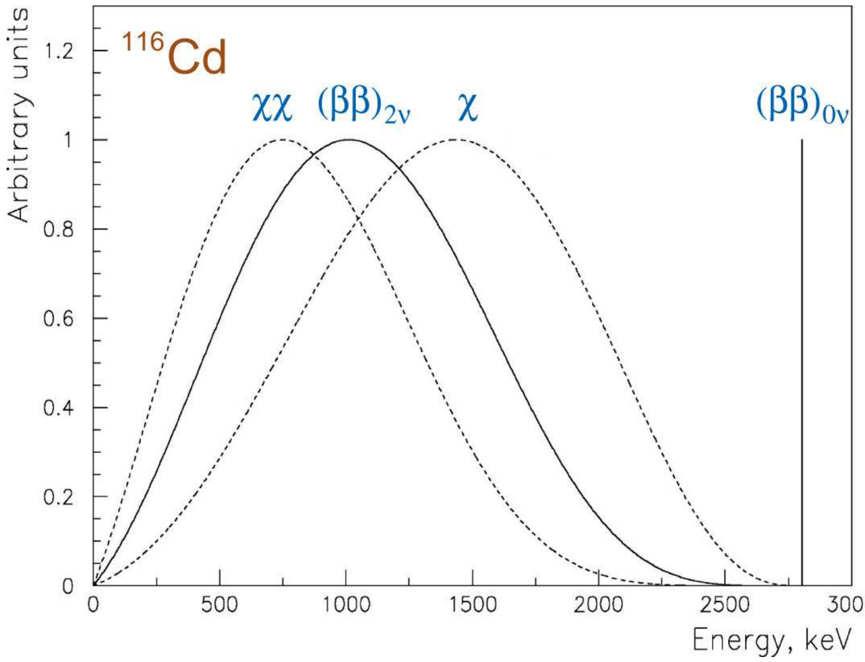


Only Majorana



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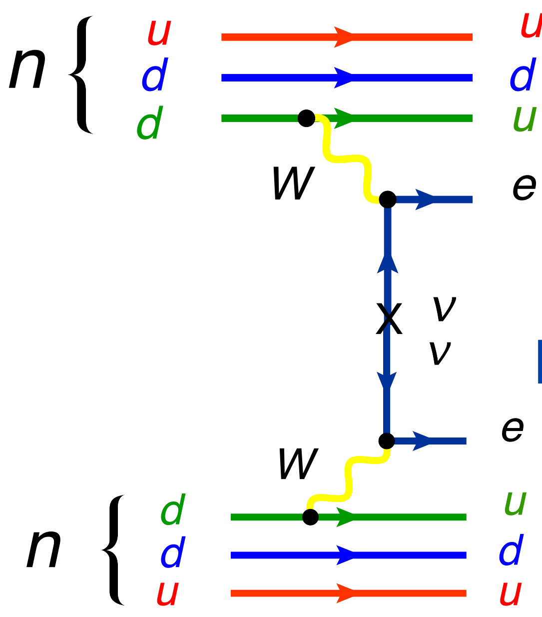
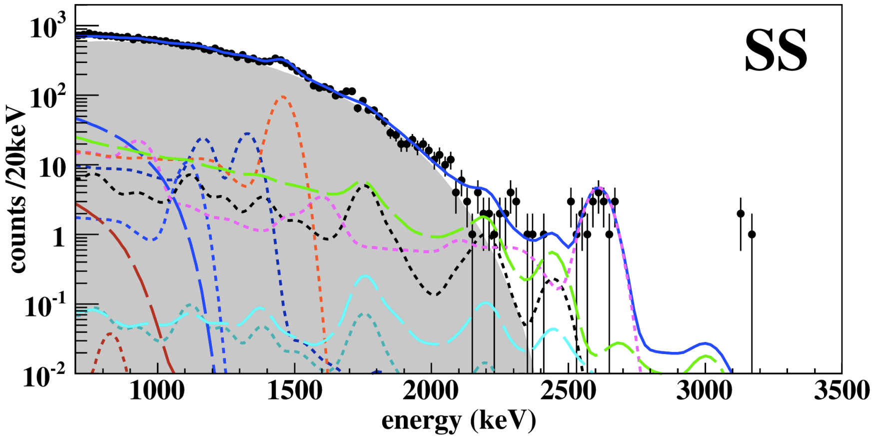
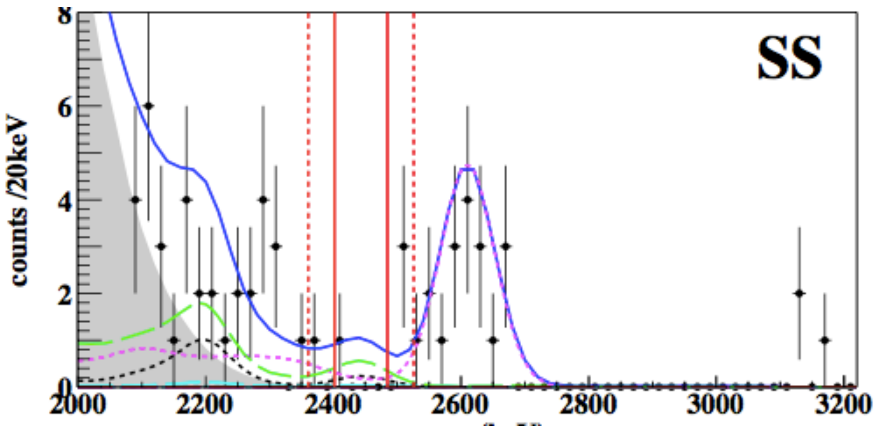


Only Majorana





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+

Neutrino Sector

Dirac or Majorana?

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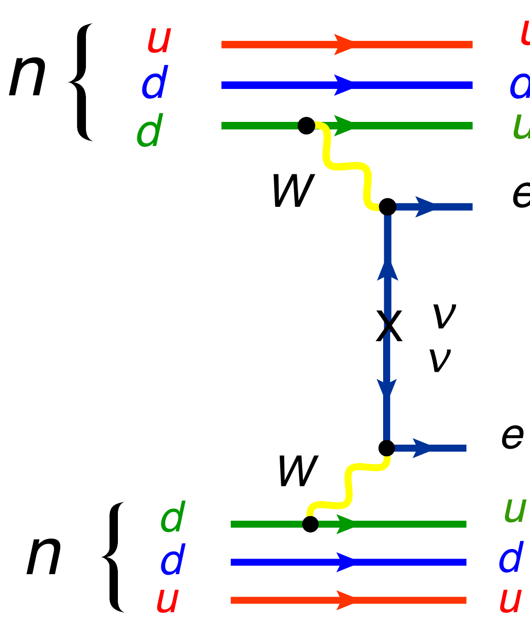
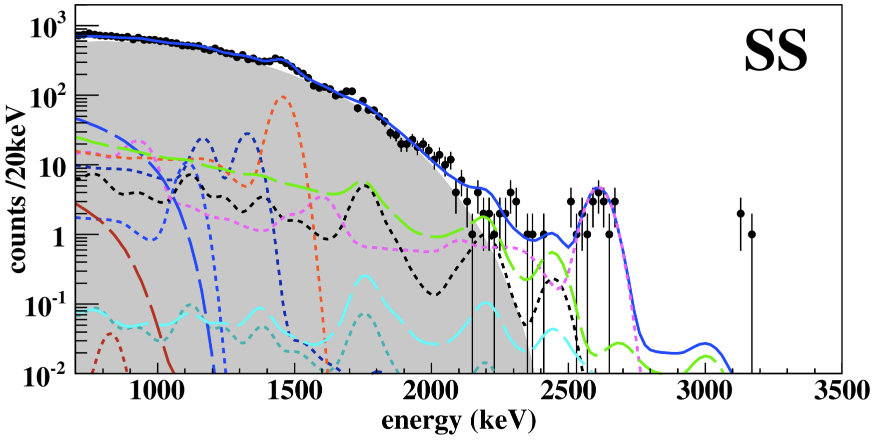
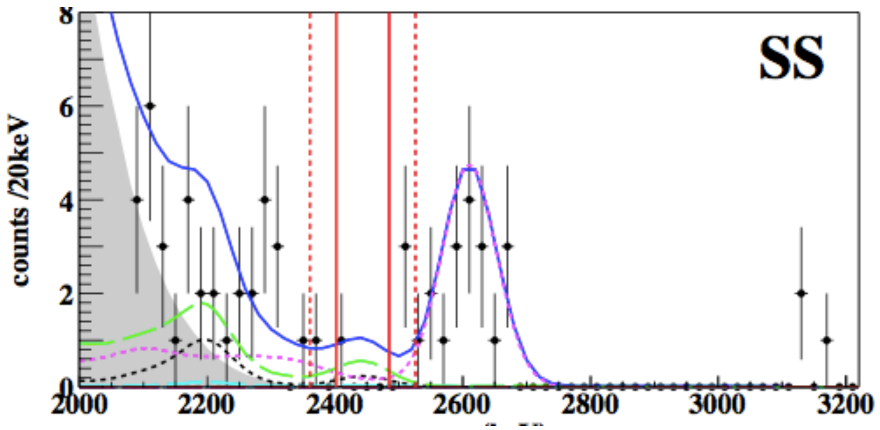


Only Majorana





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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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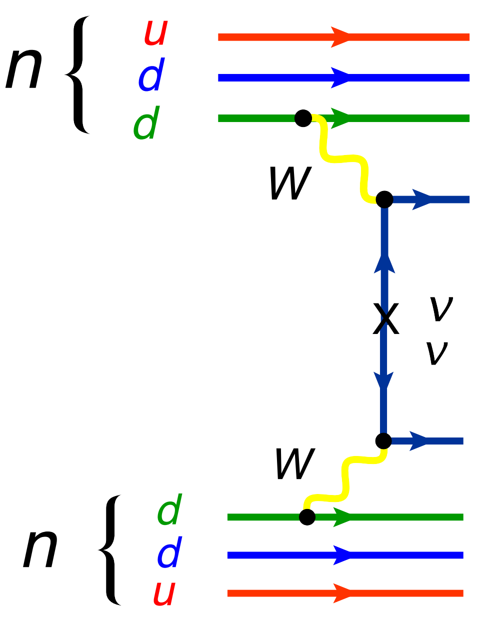
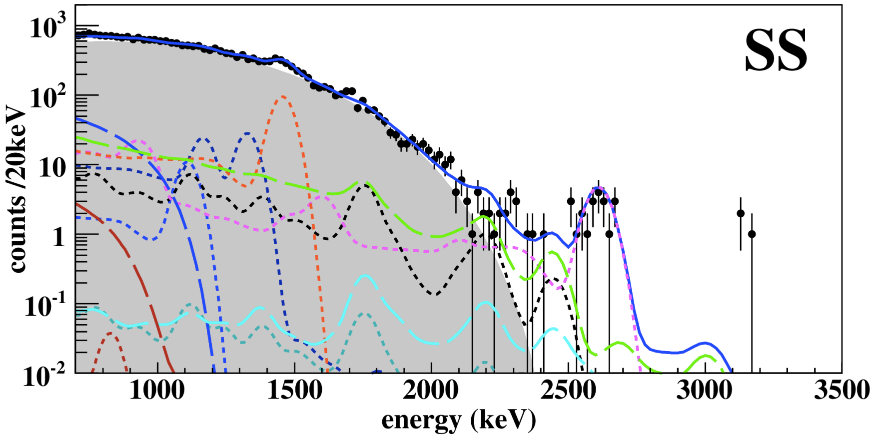
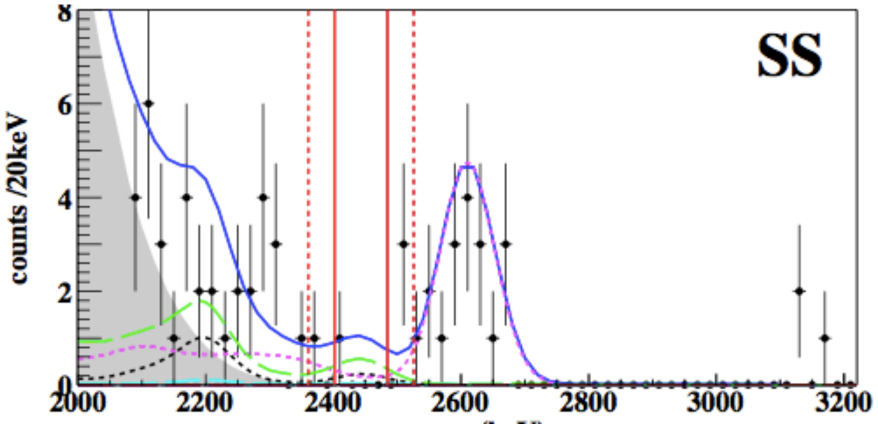
0νββ decay



Only Majorana





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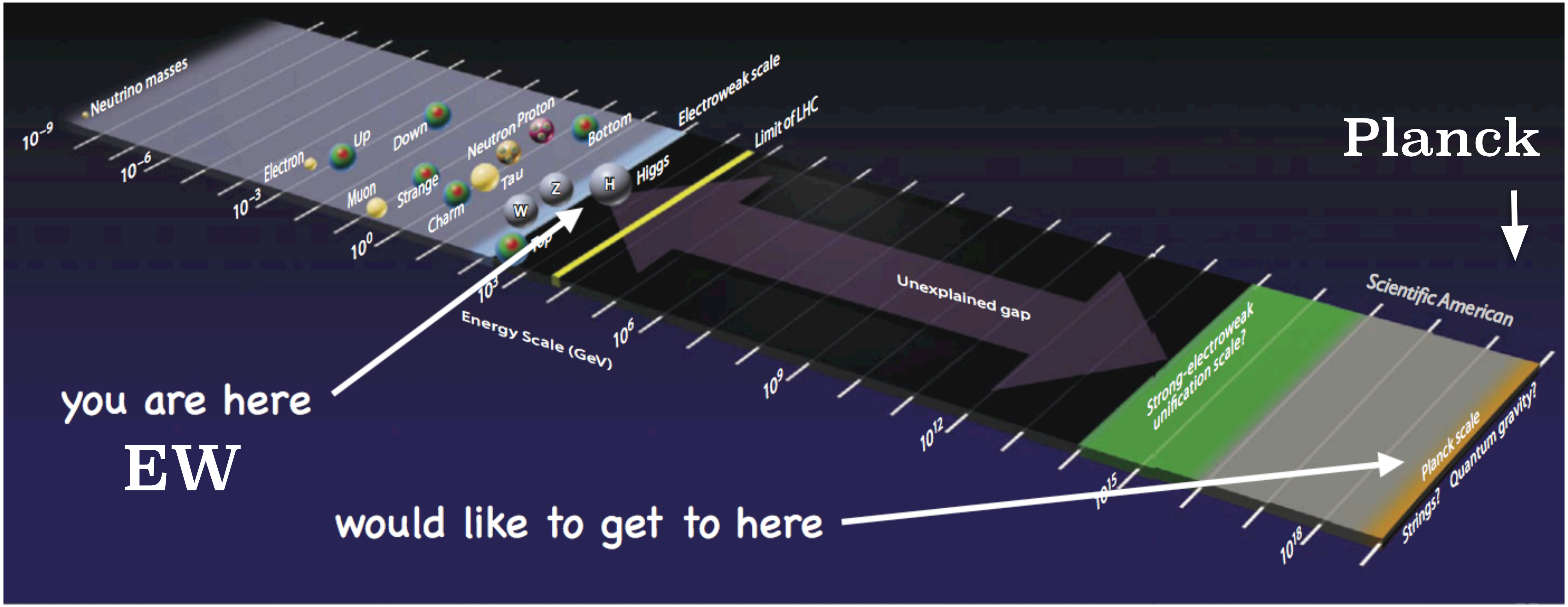
$T_{1/2}2\nu\beta\beta$ (^{136}Xe) x 10^{21} yr = 2.23 ± 0.017 stat ± 0.22 sys

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

Is there another scale except for EW and Planck?



Planck

you are here

EW

would like to get to here

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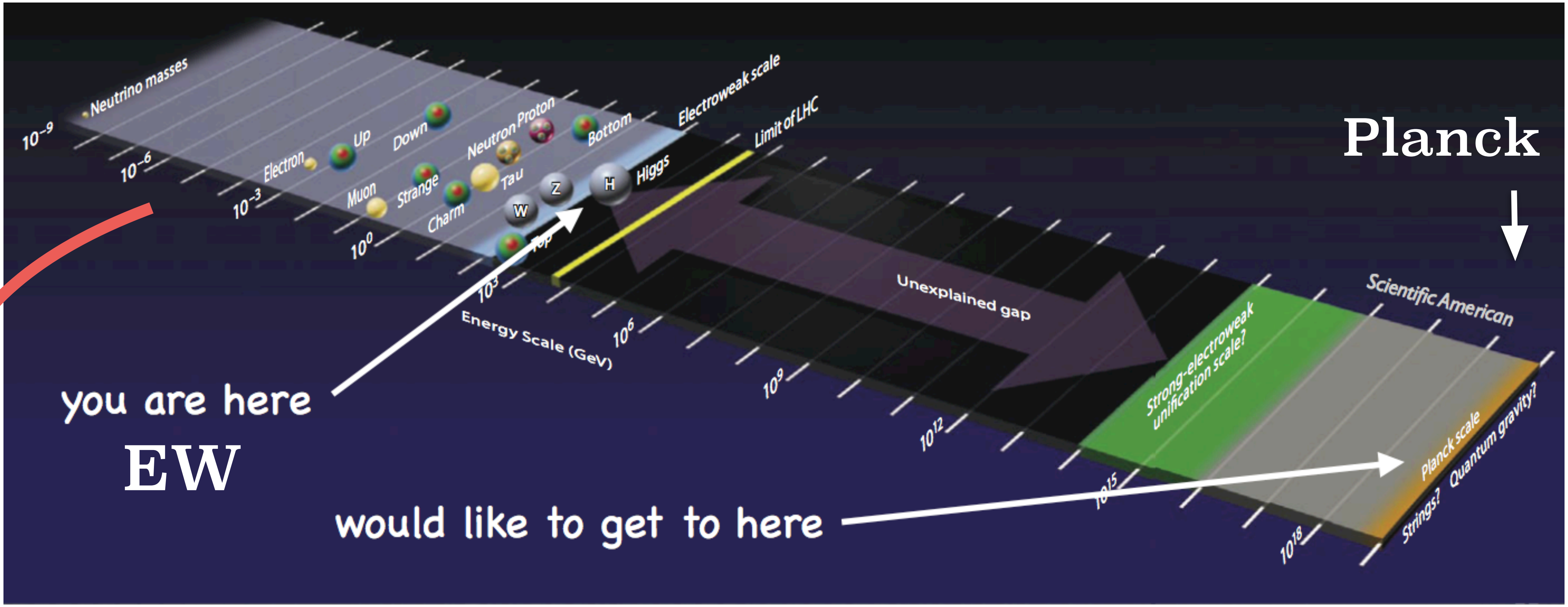
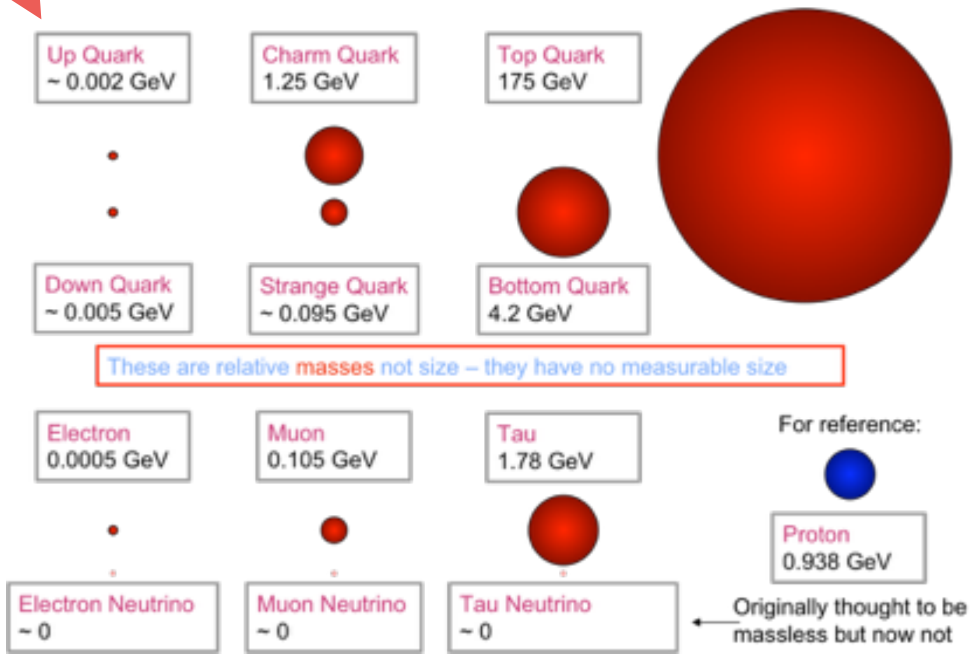


Planck

you are here

EW

would like to get to here



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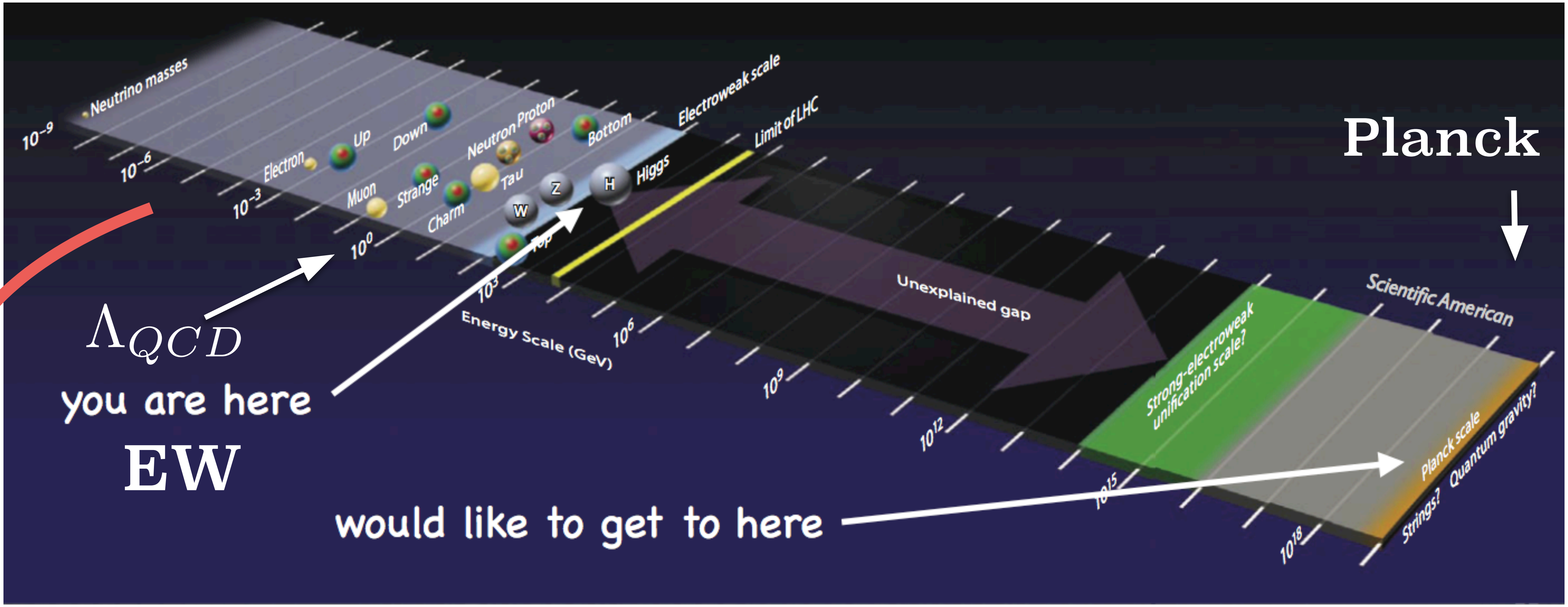


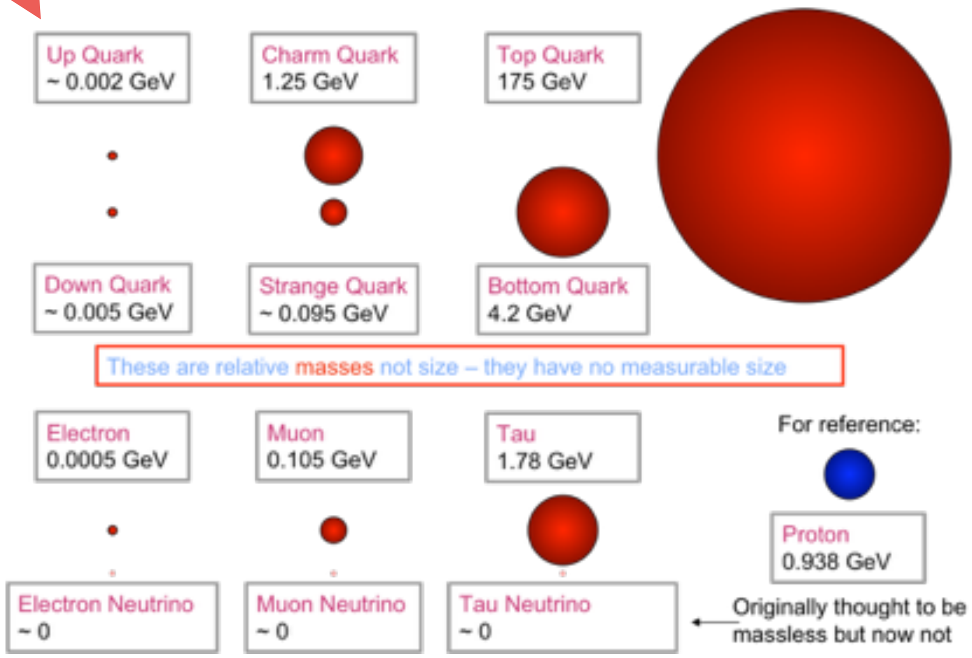
Planck

Λ_{QCD}

you are here

EW

would like to get to here



These are relative **masses** not size – they have no measurable size

For reference:

Originally thought to be massless but now not

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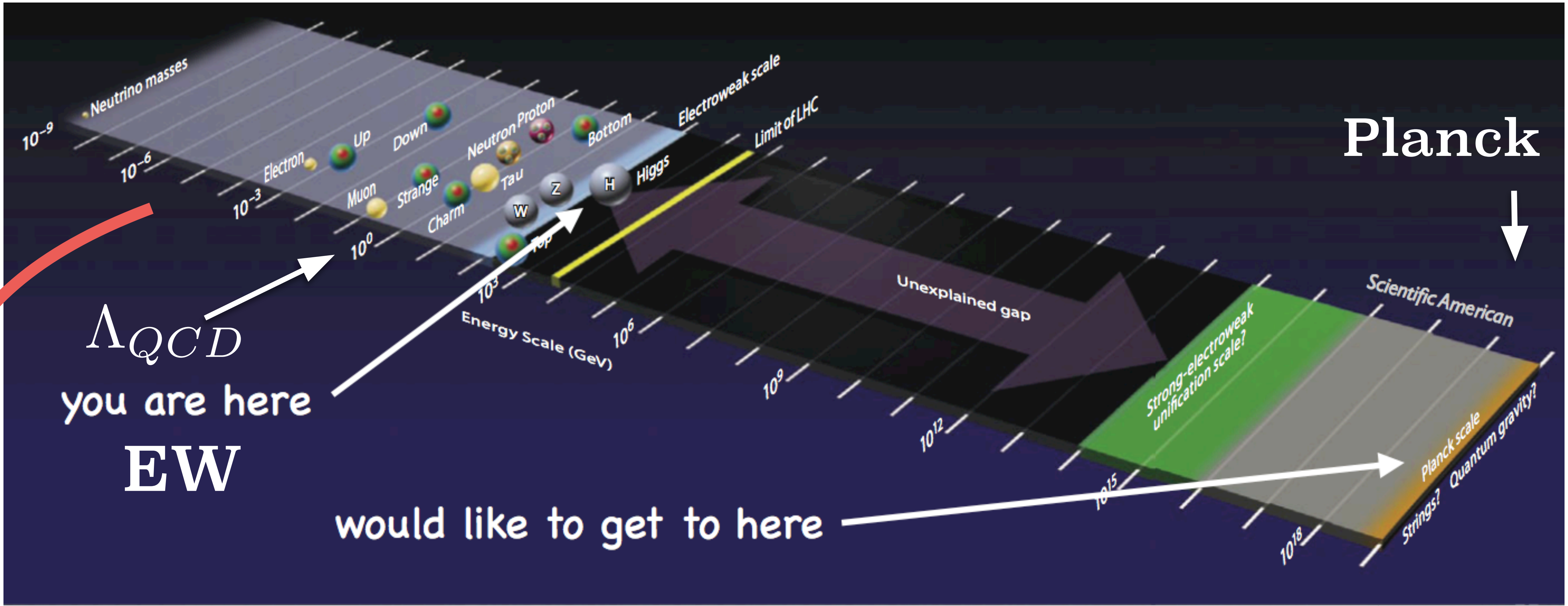

Planck

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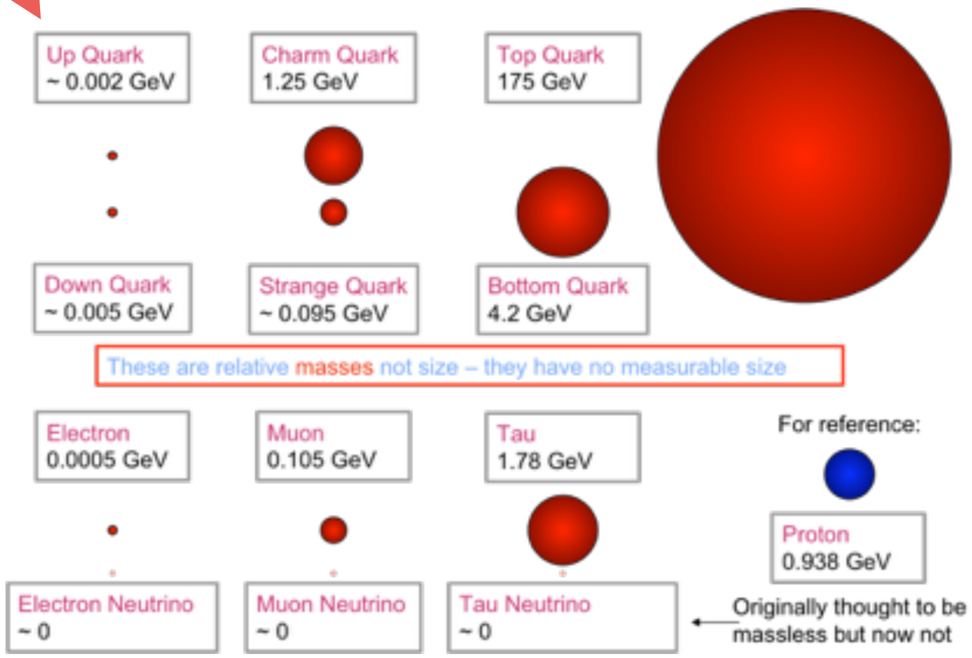
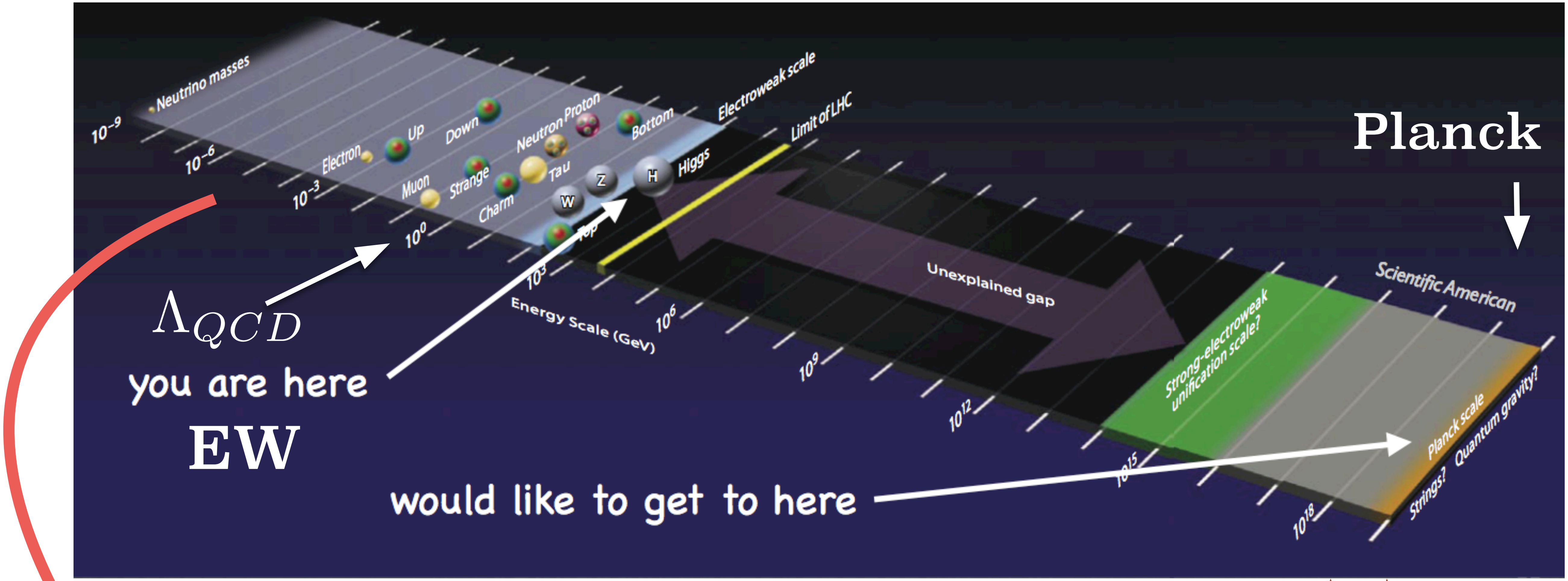


Planck scale ~ 10^{19} GeV

Is there another scale except for EW and Planck?



Planck

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EW

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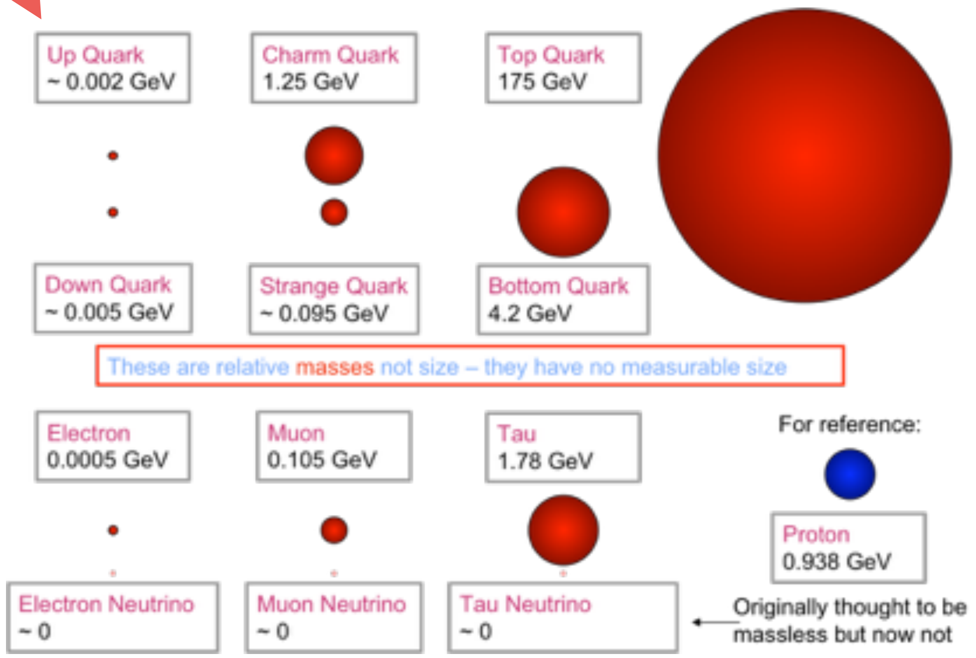
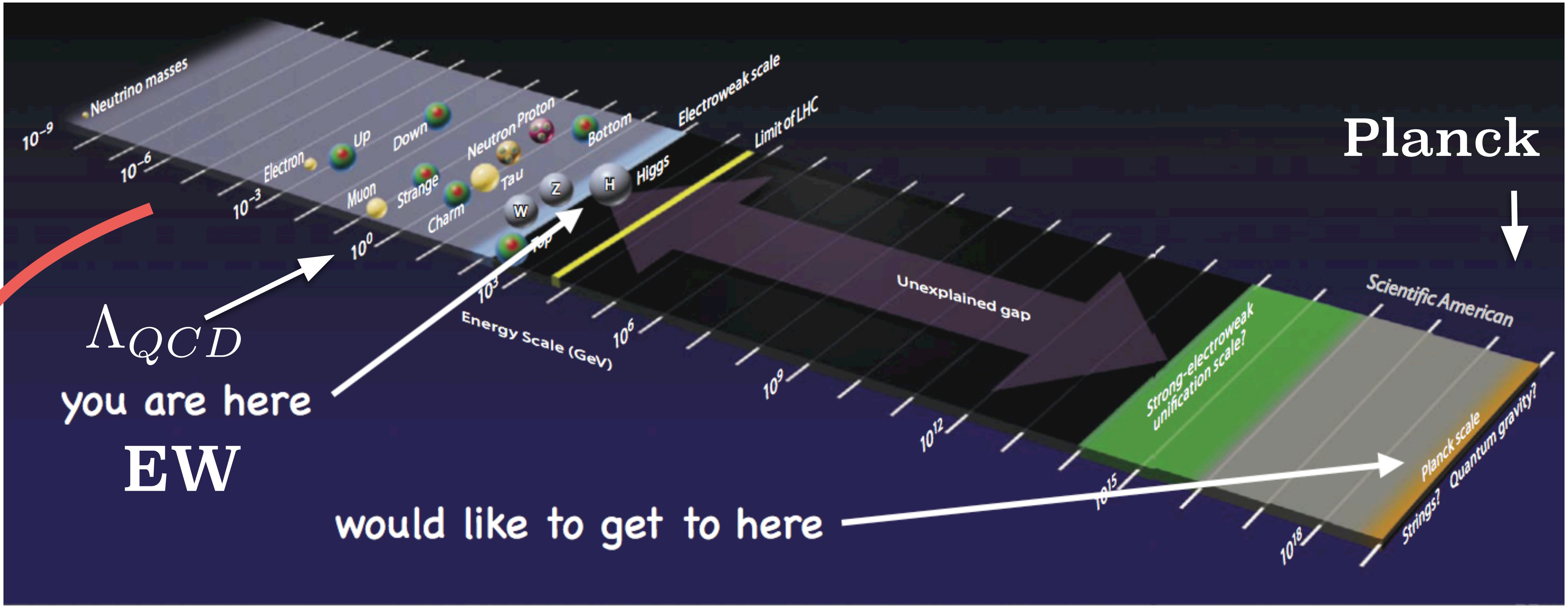


String scale ~ 10^{18} GeV

Planck scale ~ 10^{19} GeV

Is there another scale except for EW and Planck?



Planck

Λ_{QCD}

you are here

EW

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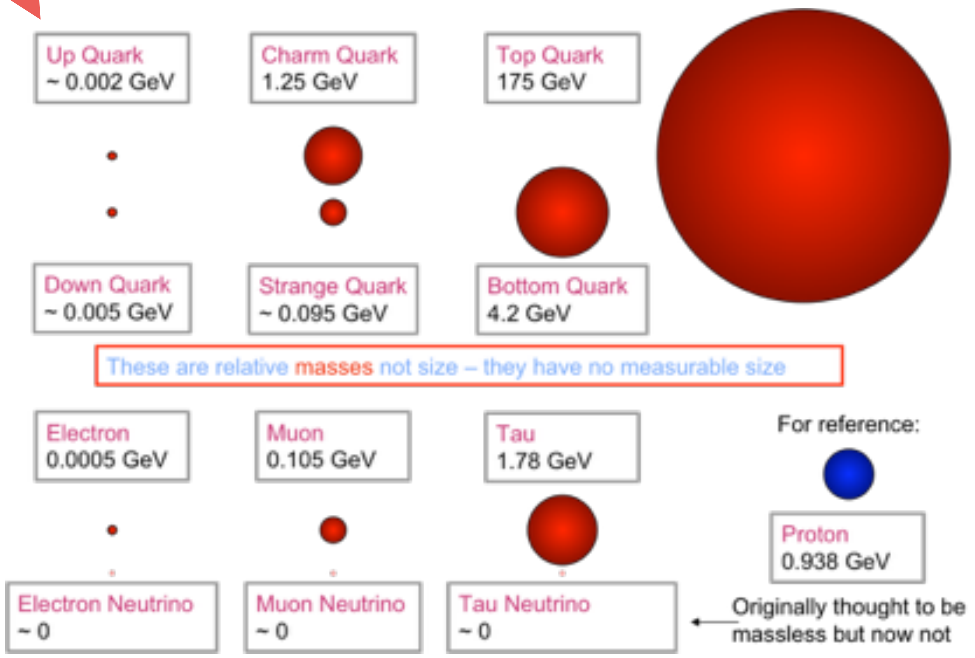
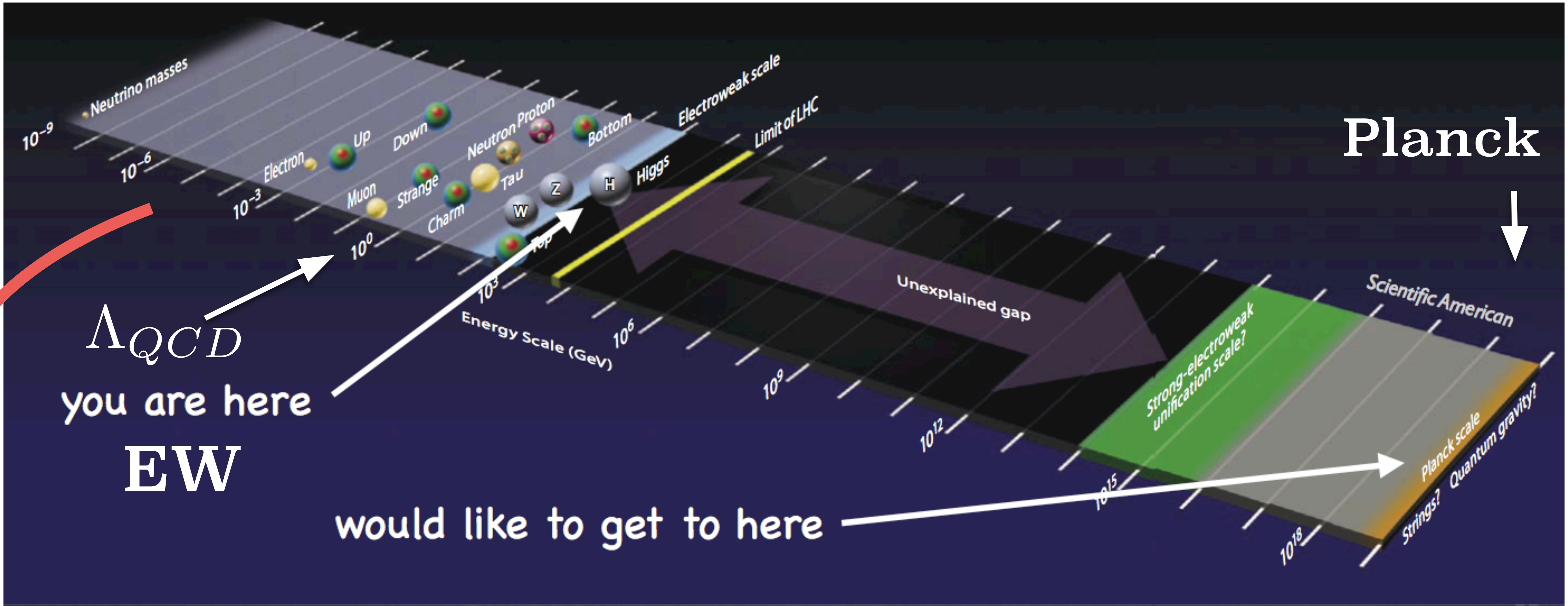


GUT scale ~ 10^{16} GeV

String scale ~ 10^{18} GeV

Planck scale ~ 10^{19} GeV

Is there another scale except for EW and Planck?



Planck

Λ_{QCD}

you are here

EW

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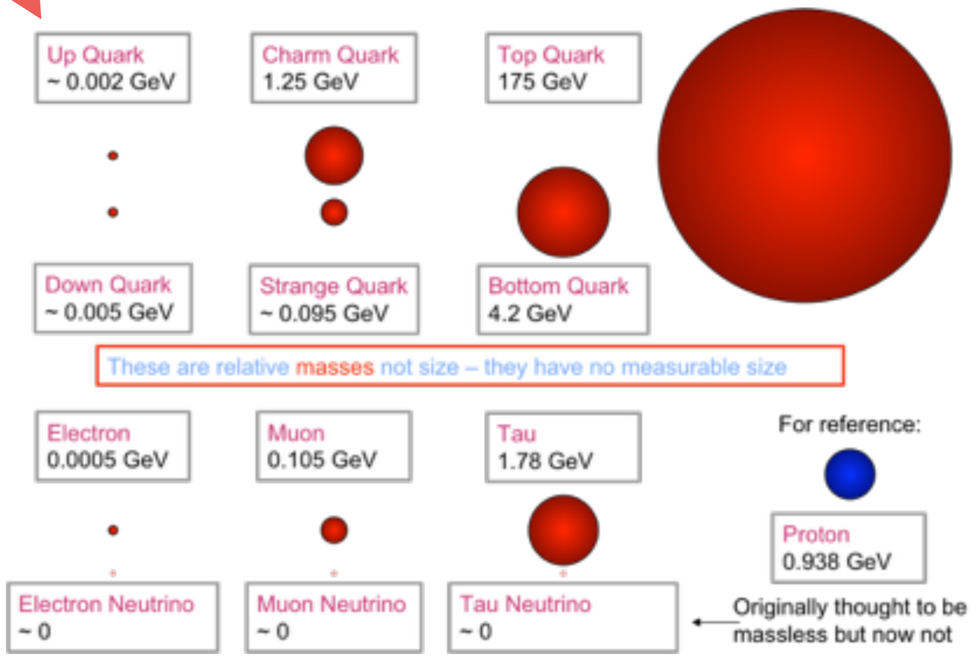

Majorana scale ~ 10^{12} GeV

GUT scale ~ 10^{16}GeV

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Planck scale ~ 10^{19}GeV

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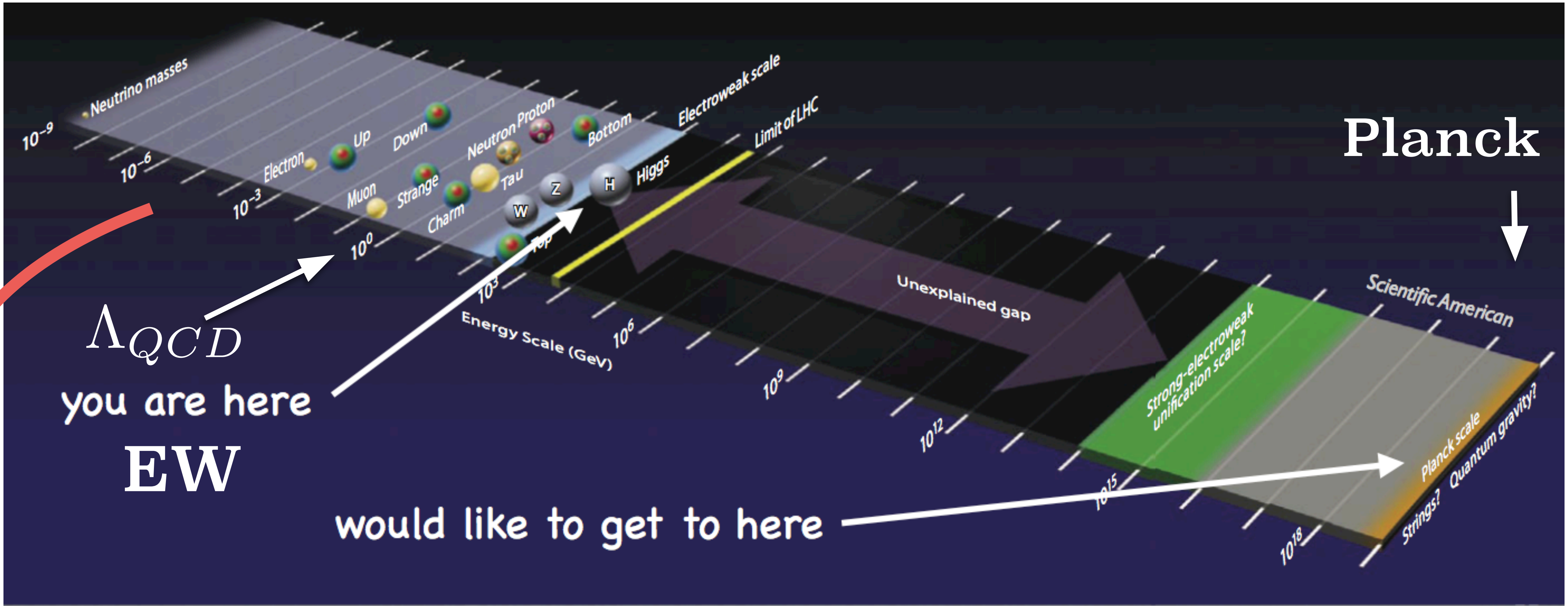

Planck

Λ_{QCD}

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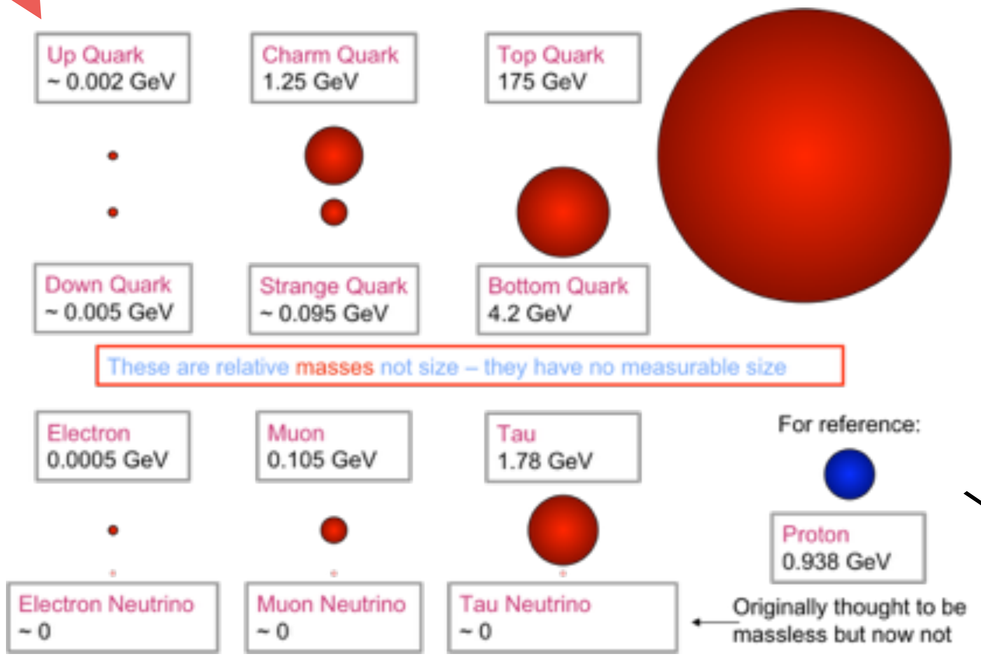
EW

would like to get to here



Vacuum Stab ~ 10^{11}GeV

Majorana scale ~ 10^{12} GeV

GUT scale ~ 10^{16}GeV

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Planck scale ~ 10^{19}GeV

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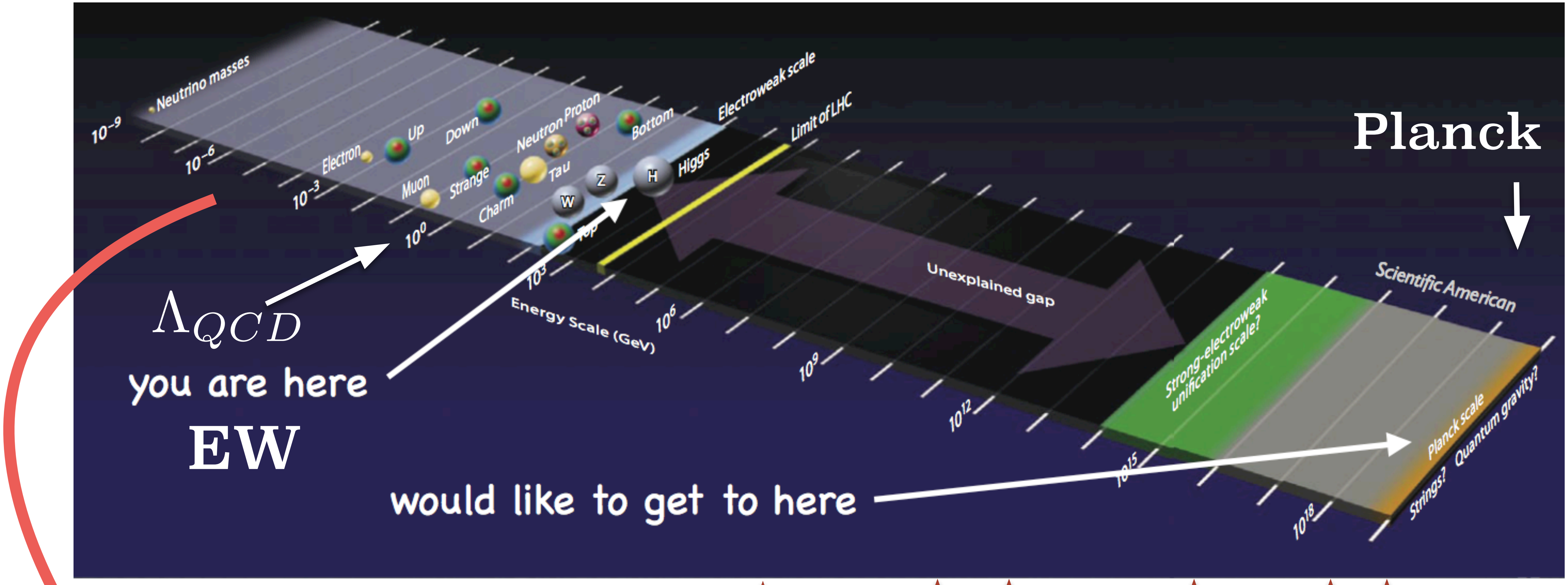

Planck

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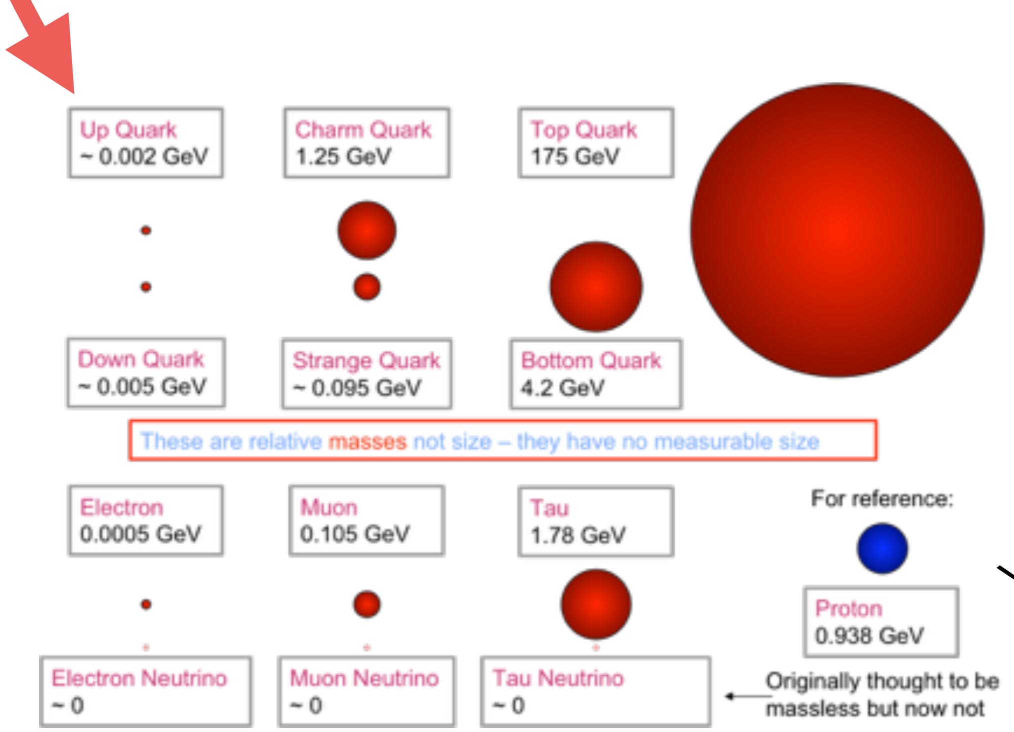

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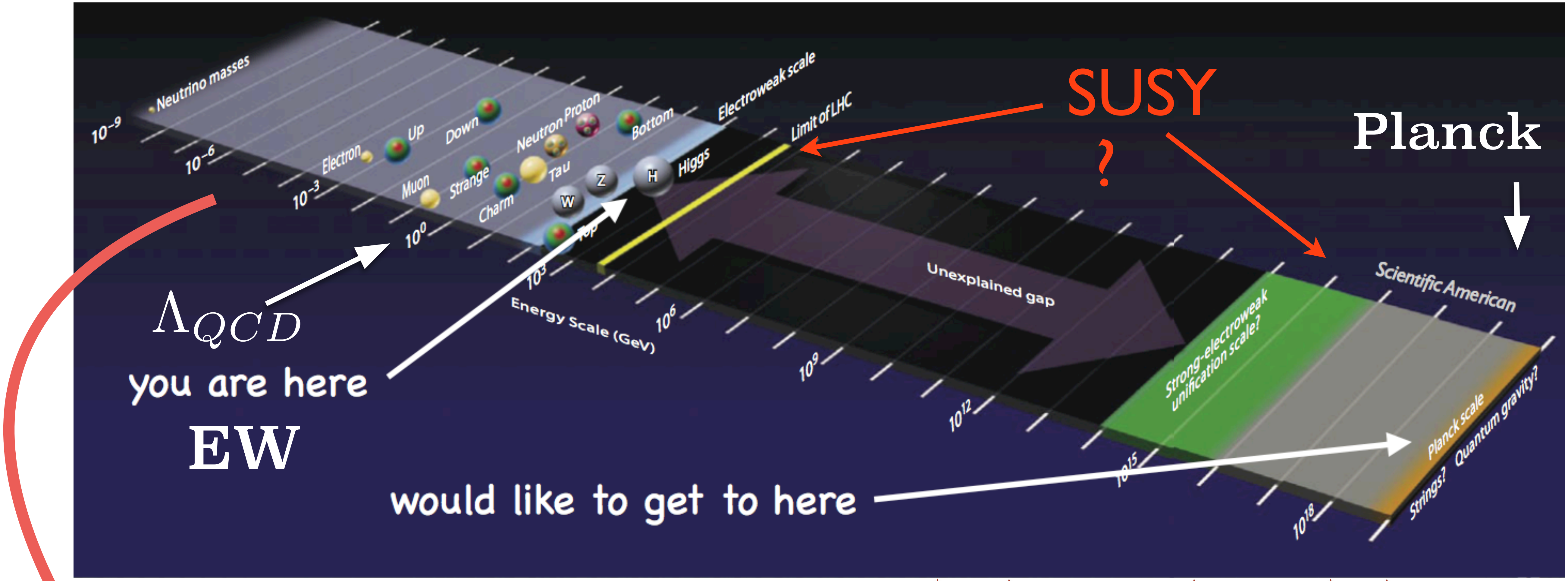


SUSY

?

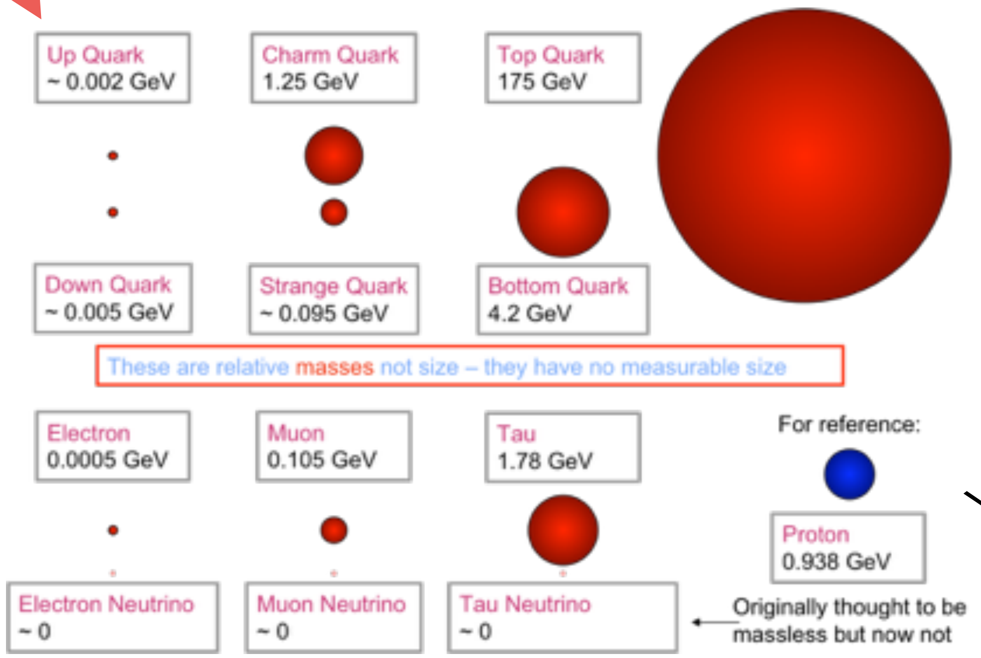
Planck

Λ_{QCD}

you are here

EW

would like to get to here



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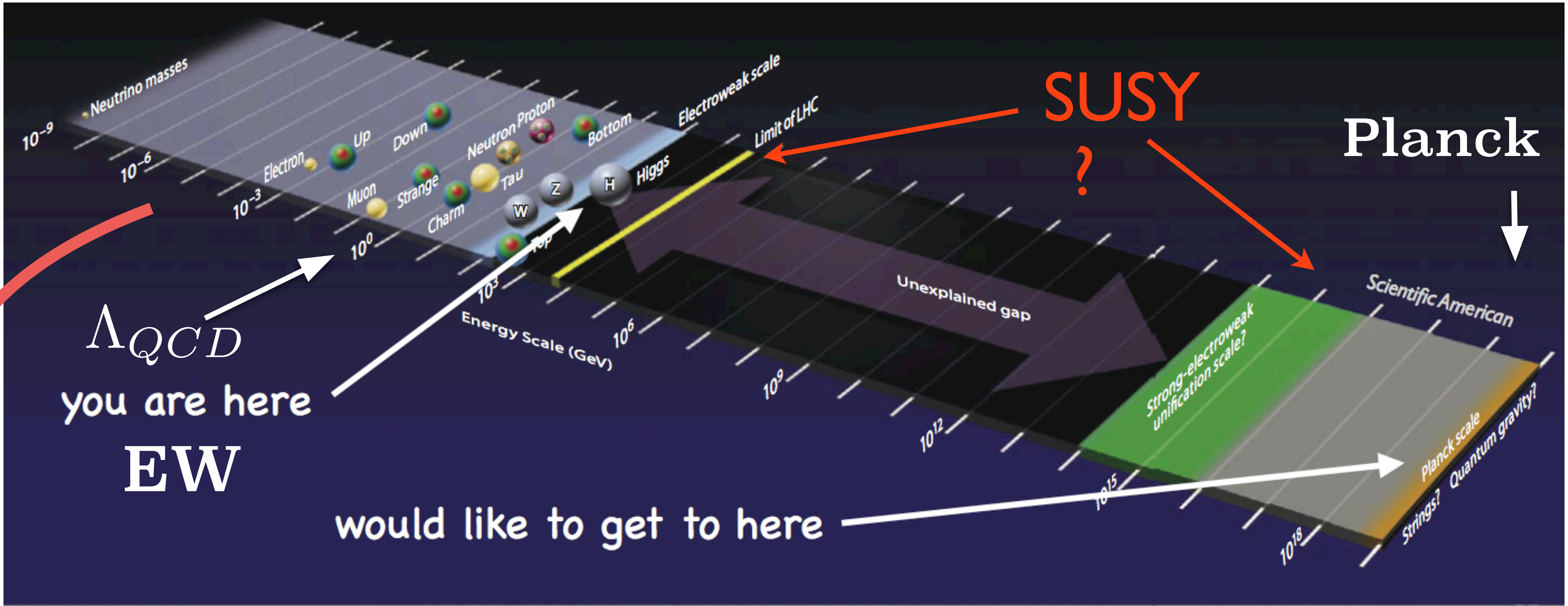

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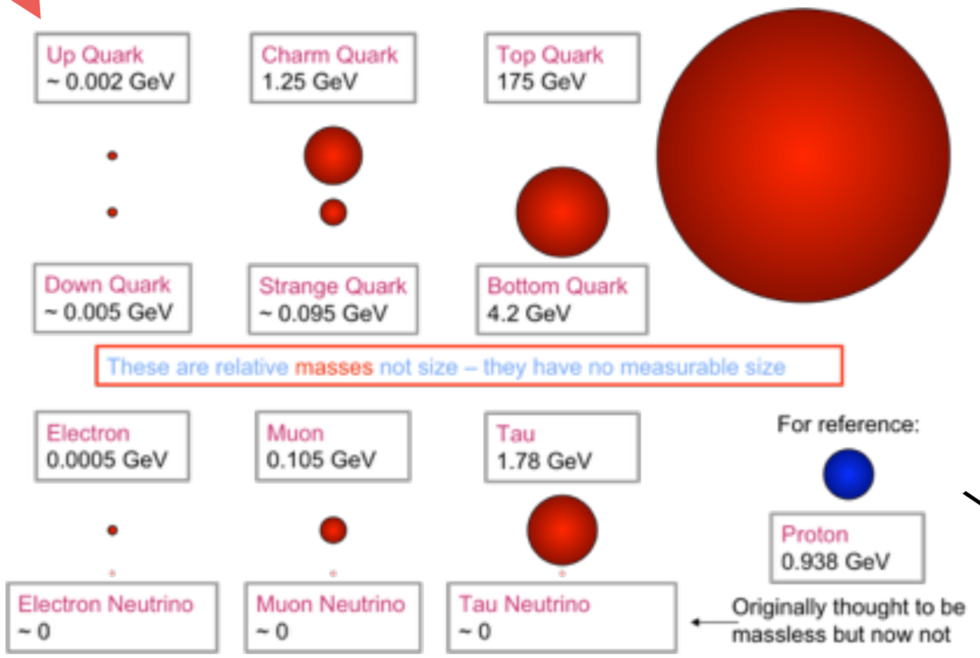

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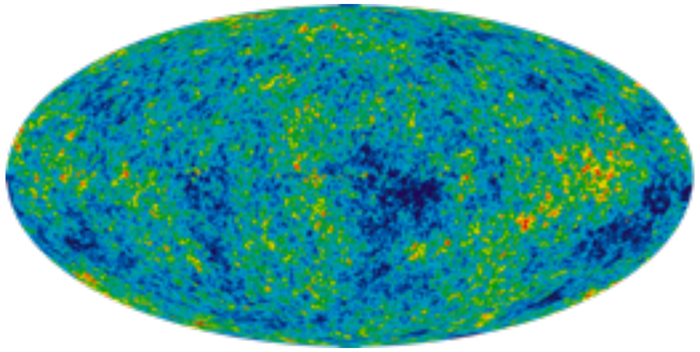
Is it compatible with Cosmology?



Astrophysics & Cosmology challenge

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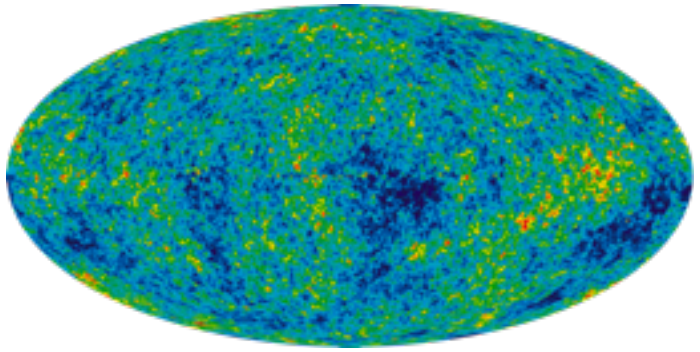

Astrophysics & Cosmology challenge

- Baryon asymmetry of the Universe

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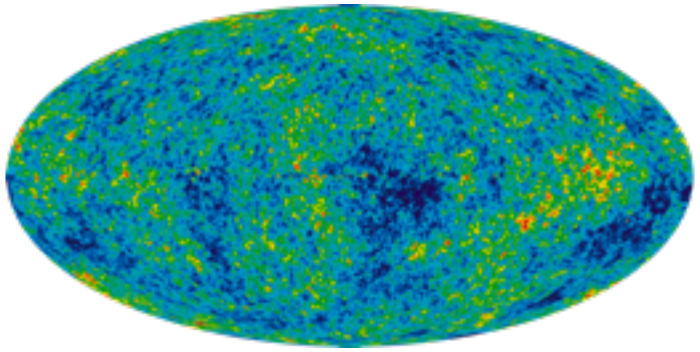

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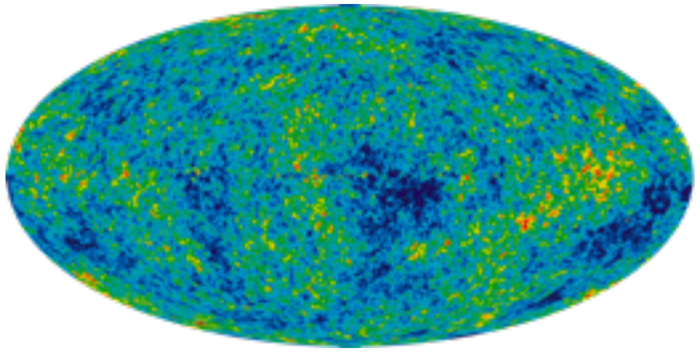
- Baryon asymmetry of the Universe

$$\frac{N(B)-N(\bar{B})}{N_\gamma} \sim (6.19 \pm 0.14) \times 10^{-10}$$

Is it compatible with Cosmology?



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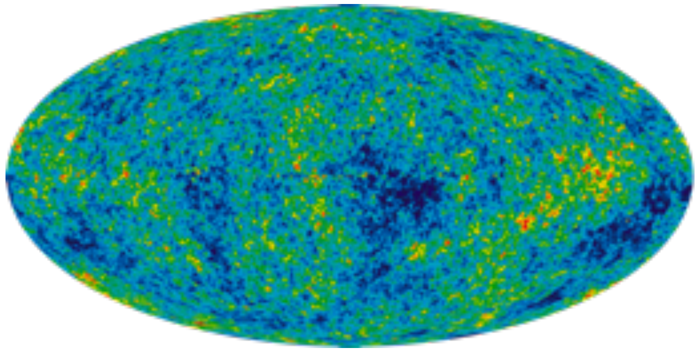
- still not explained
- requires larger $\cancel{CP}$ than in the SM

Is it compatible with Cosmology?



Astrophysics & Cosmology challenge

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$$\frac{N(B) - N(\bar{B})}{N_\gamma} \sim (6.19 \pm 0.14) \times 10^{-10}$$

- Relic abundance of the Dark Matter

$$OM = 4.9\%, \;\; DM = 26.8\%, \;\; DE = 68.3\%$$

- still not explained
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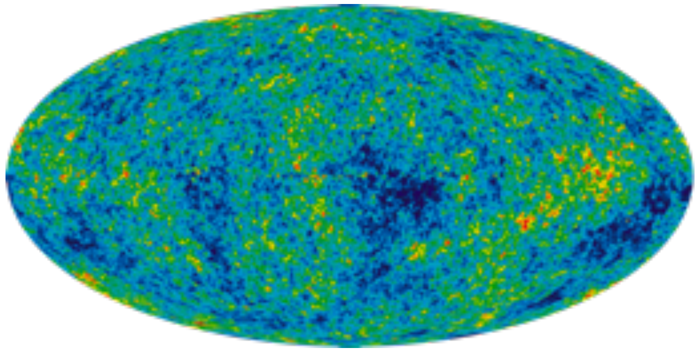
Is it compatible with Cosmology?



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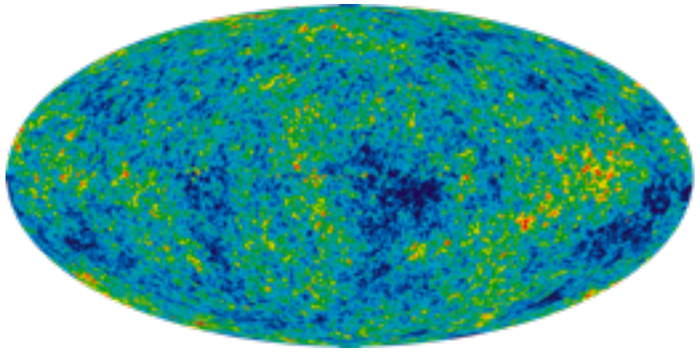

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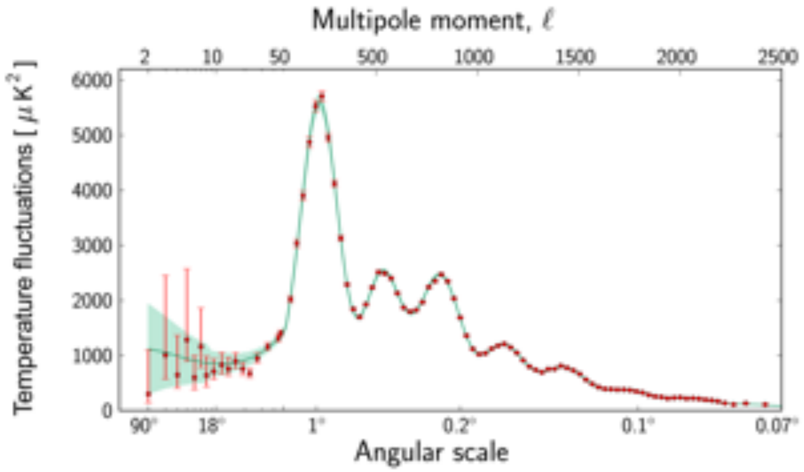
$$OM = 4.9\%,\ DM = 26.8\%,\ DE = 68.3\%$$

- Understanding is beyond the SM

- Number of neutrinos

$$N_{eff} = 3.52 \pm 0.47 \quad 95\%\ CL$$
$$Planck + WP + highL + BAO + HST$$



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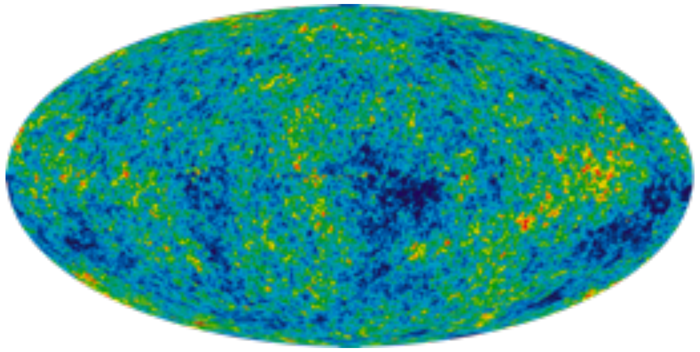

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- Relic abundance of the Dark Matter

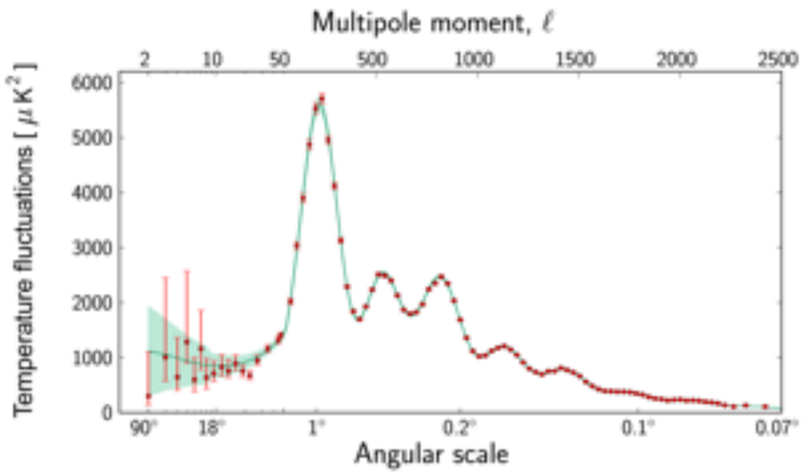
$$OM = 4.9\%,\ DM = 26.8\%,\ DE = 68.3\%$$

- Understanding is beyond the SM

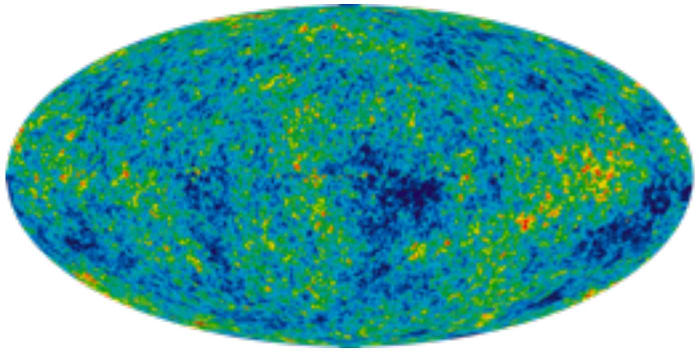
- Number of neutrinos

$$N_{eff} = 3.52 \pm 0.47 \quad 95\%\ CL$$
$$Planck + WP + highL + BAO + HST$$

- Well suits the SM
  q <-> l



Is it compatible with Cosmology?



Astrophysics & Cosmology challenge

- Baryon asymmetry of the Universe

$$\frac{N(B)-N(\bar{B})}{N_\gamma} \sim (6.19 \pm 0.14) \times 10^{-10}$$

- still not explained
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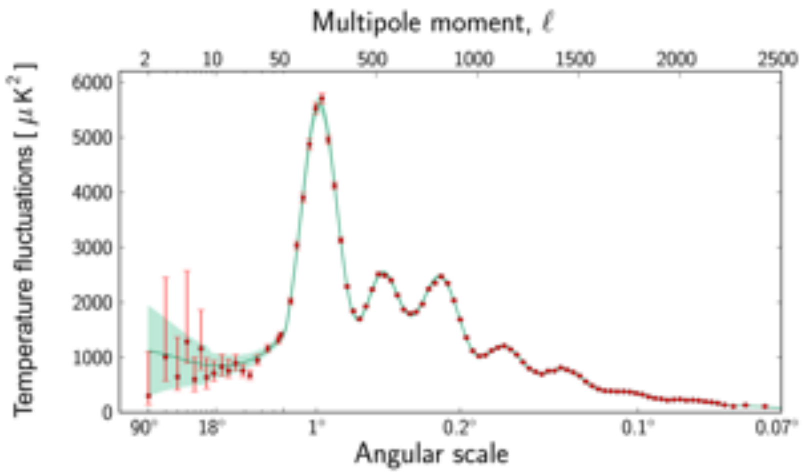

- Masses of neutrinos

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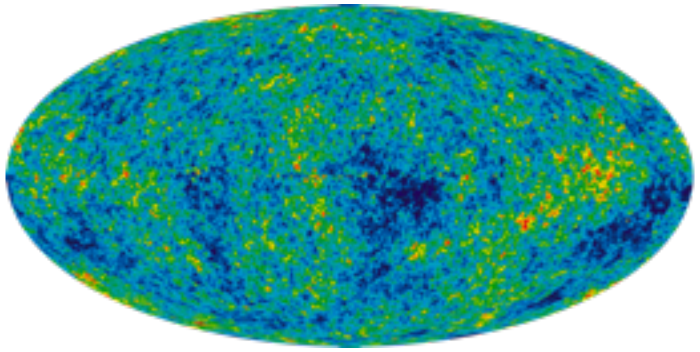

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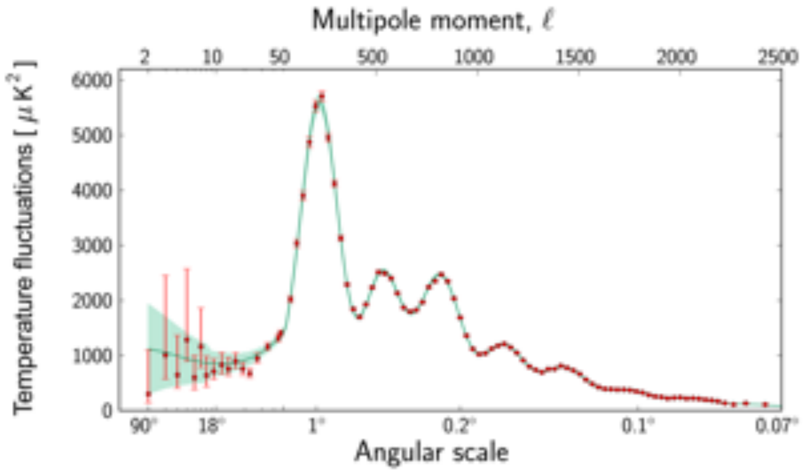
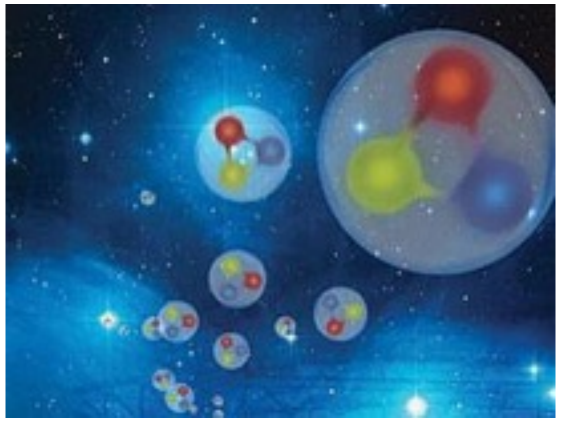
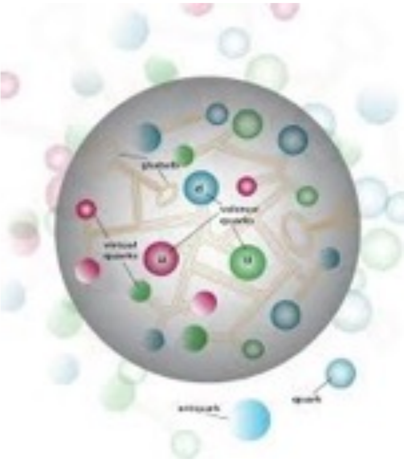


Do we understand confinement?

Challenging problem in particle physics well inside the SM





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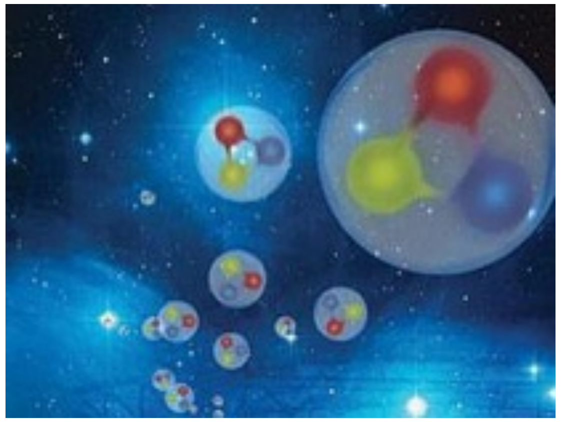

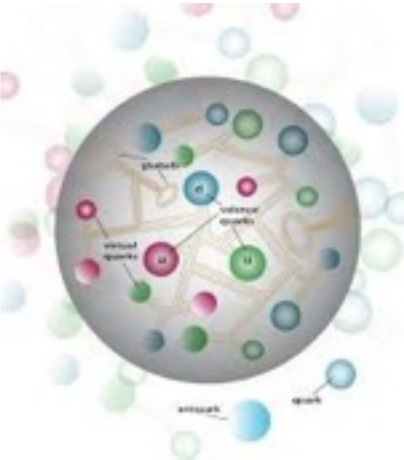

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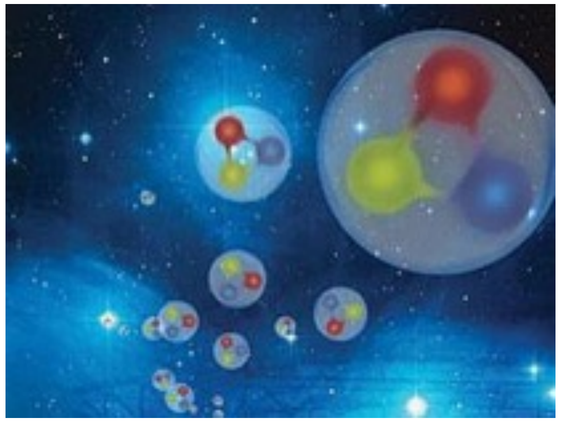
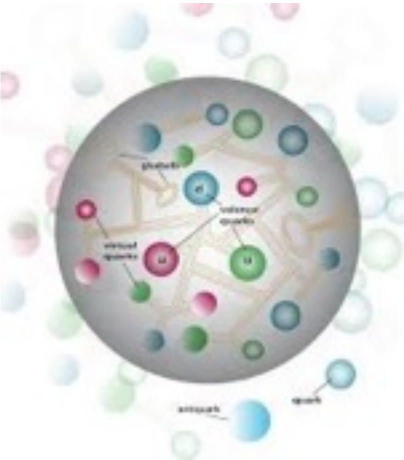


- How confinement actually works?
- Why colourless states?
- Which bound states exist in Nature?



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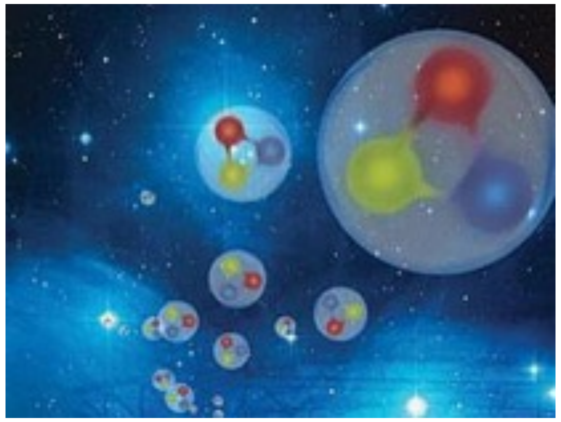

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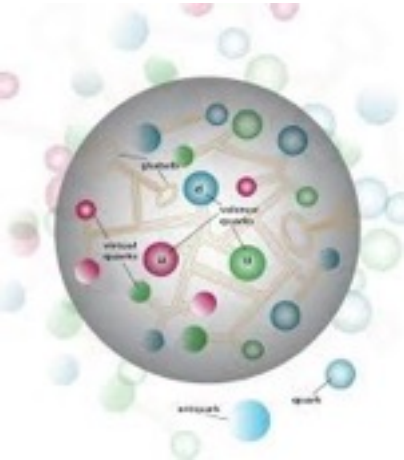

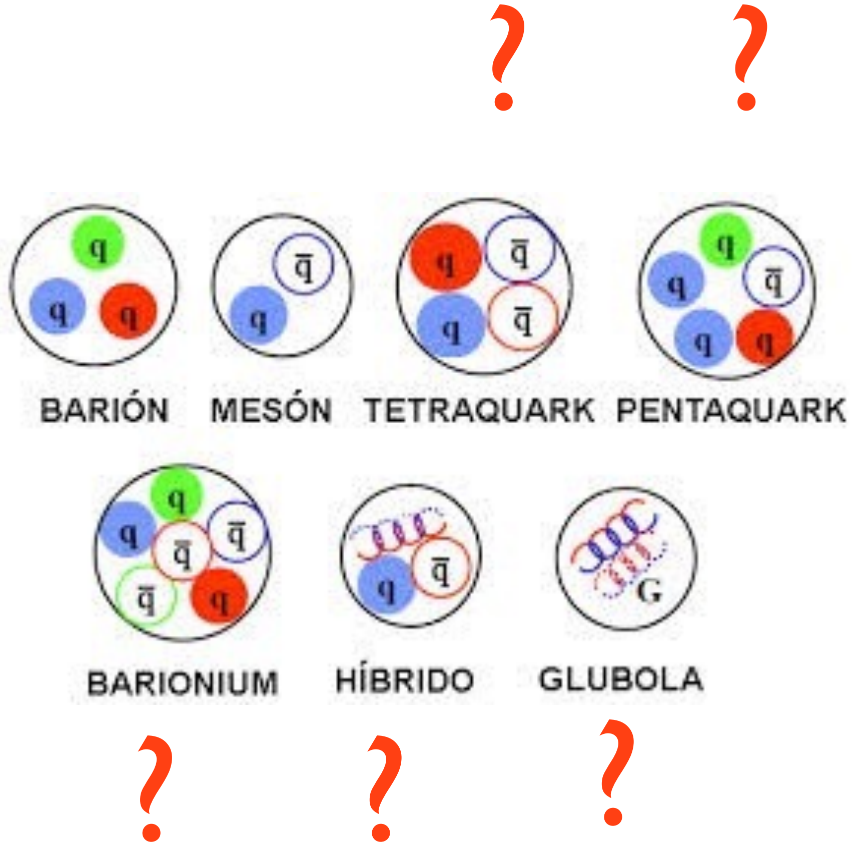

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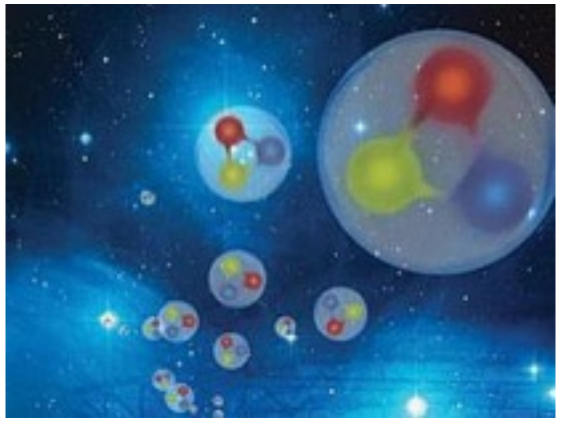

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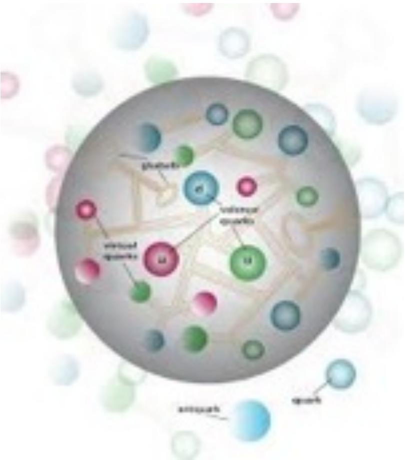

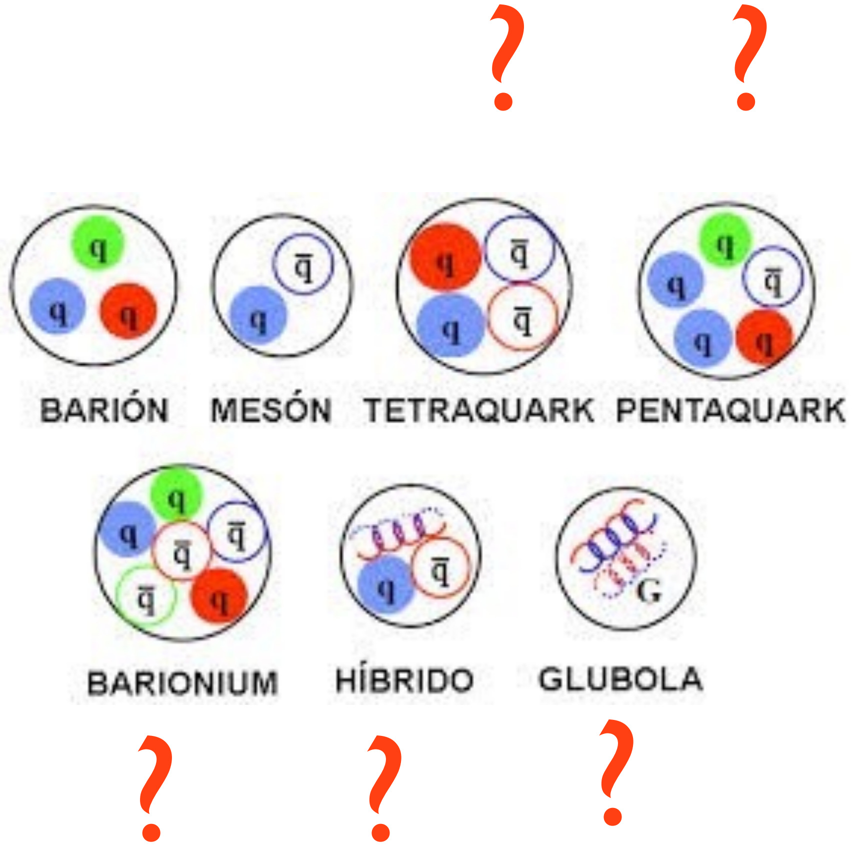

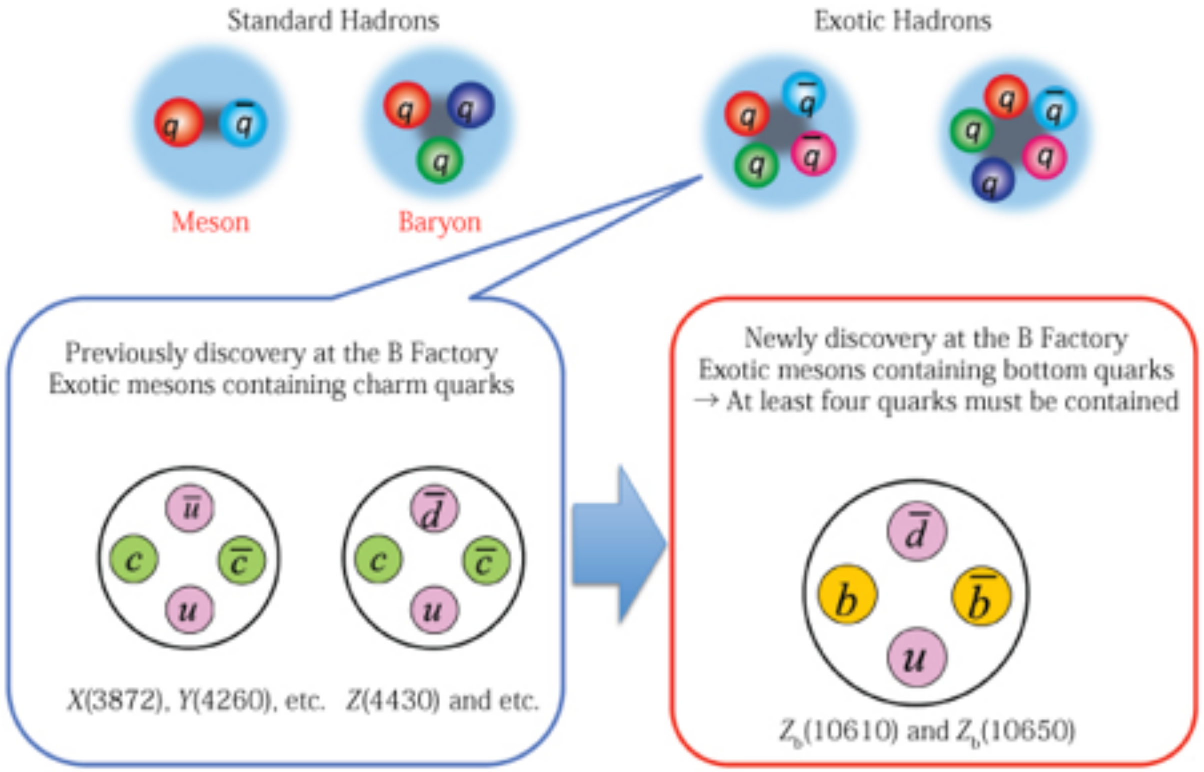

Previously discovery at the B Factory
Exotic mesons containing charm quarks

$X(3872)$, $Y(4260)$, etc. $Z(4430)$ and etc.

Newly discovery at the B Factory
Exotic mesons containing bottom quarks
→ At least four quarks must be contained

$Z_b(10610)$ and $Z_b(10650)$

Do we understand confinement?

Challenging problem in particle physics well inside the SM

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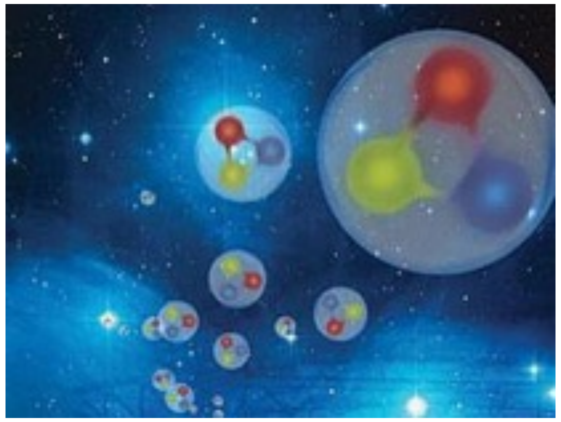

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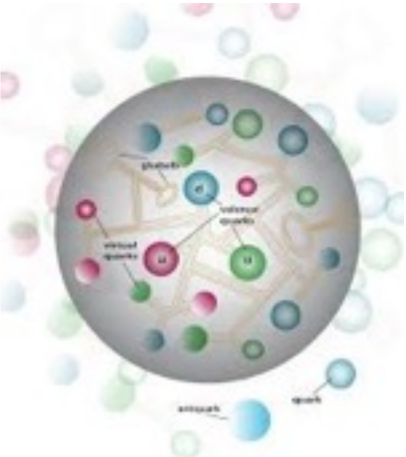
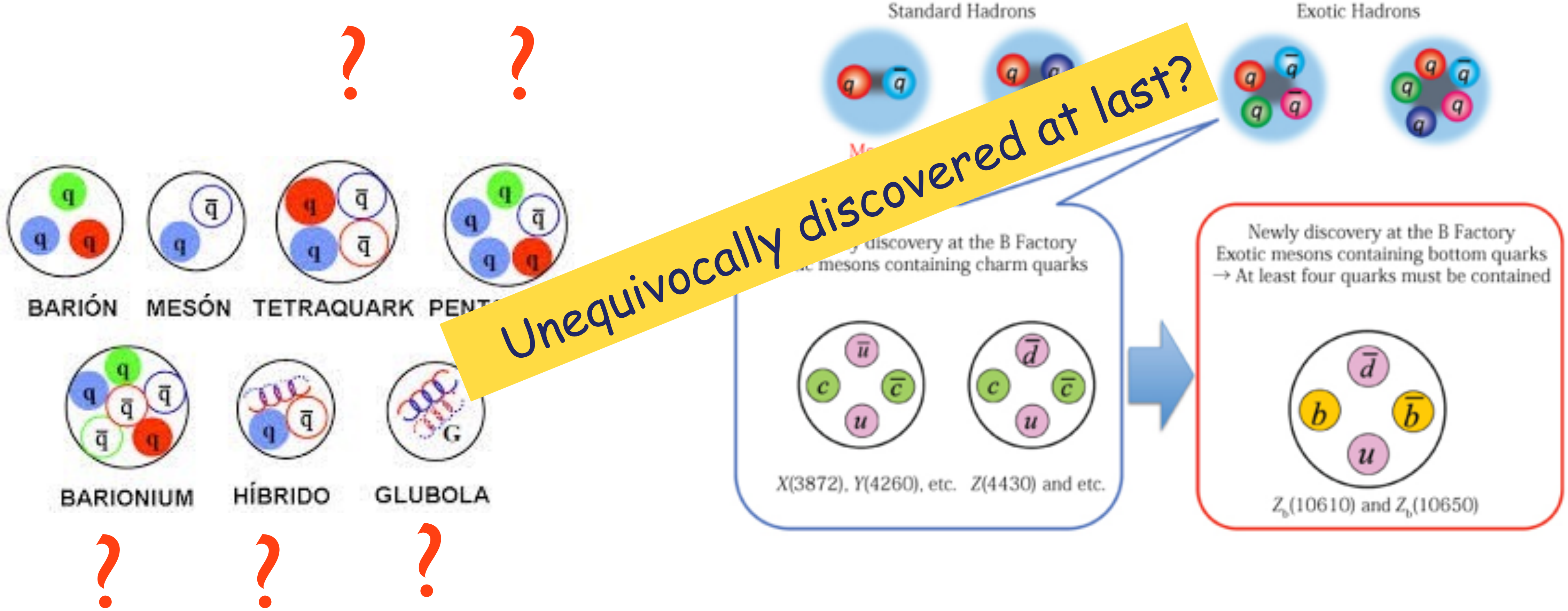


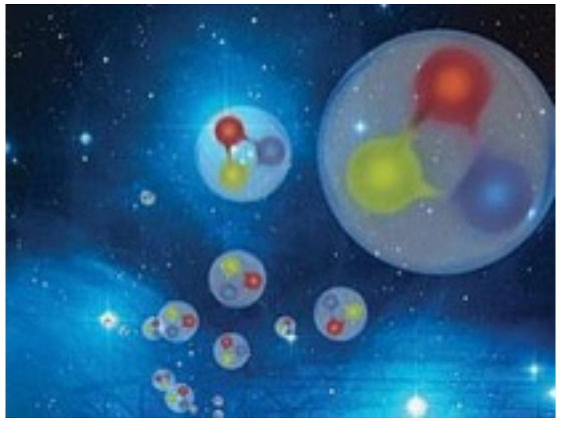


Unequivocally discovered at last?

Do we understand confinement?

Challenging problem in particle physics well inside the SM

Time to come back?



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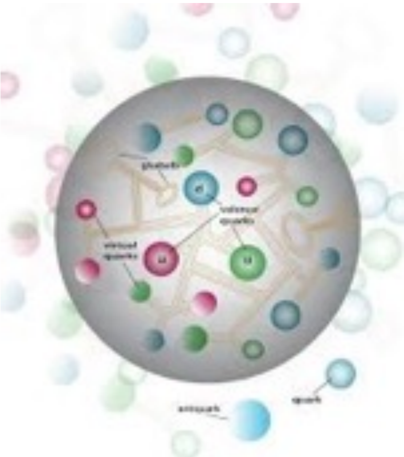

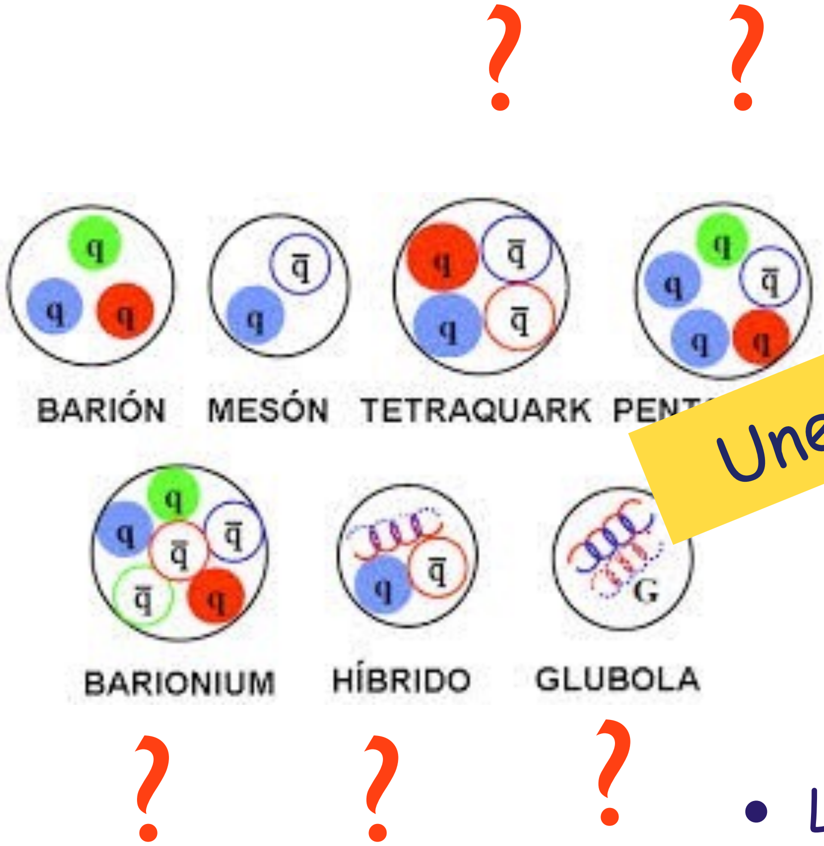

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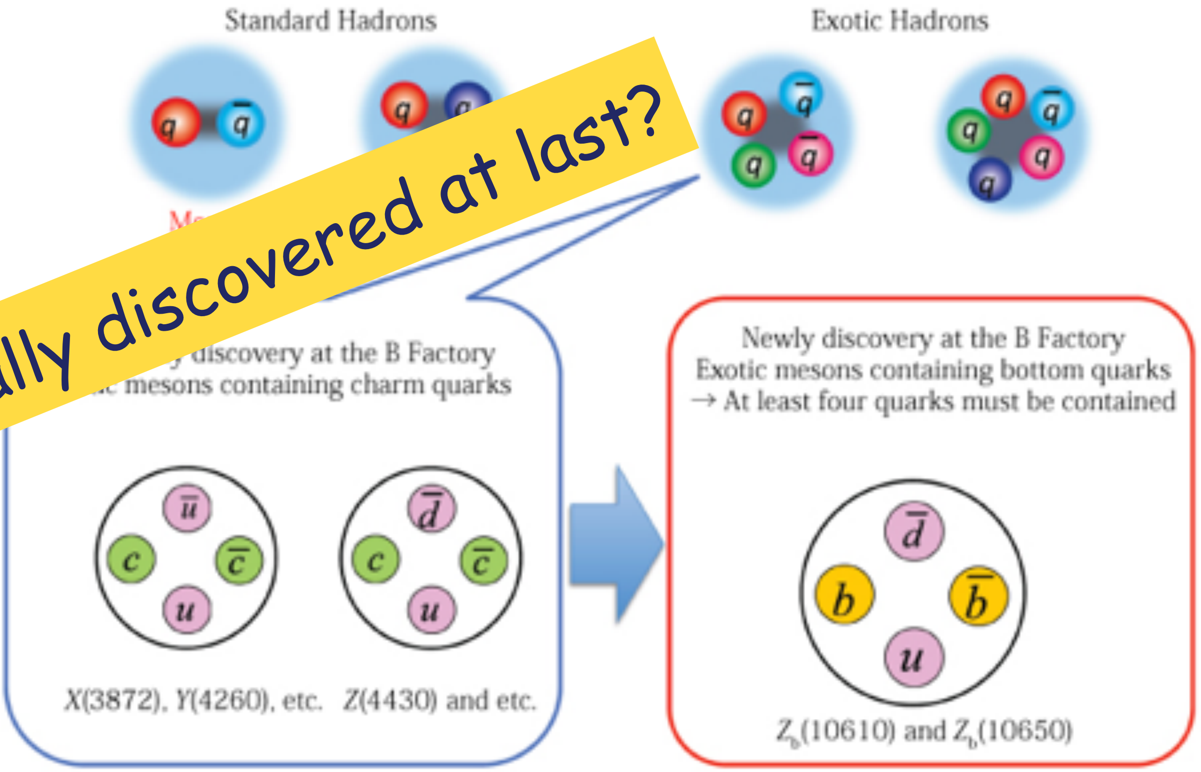

- Lattice gauge theories
- Holographic approach

Do we understand confinement?

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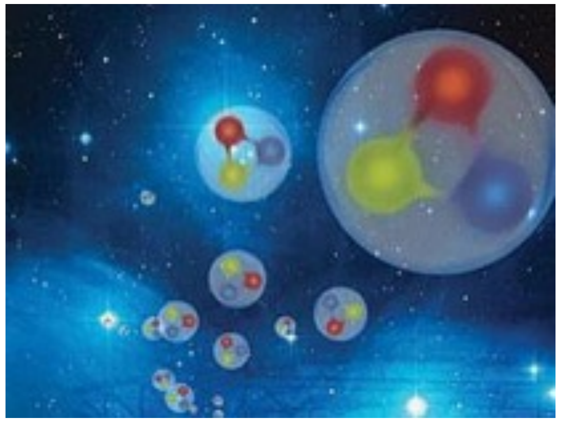

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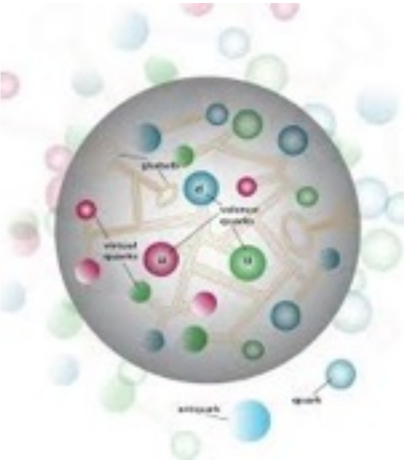

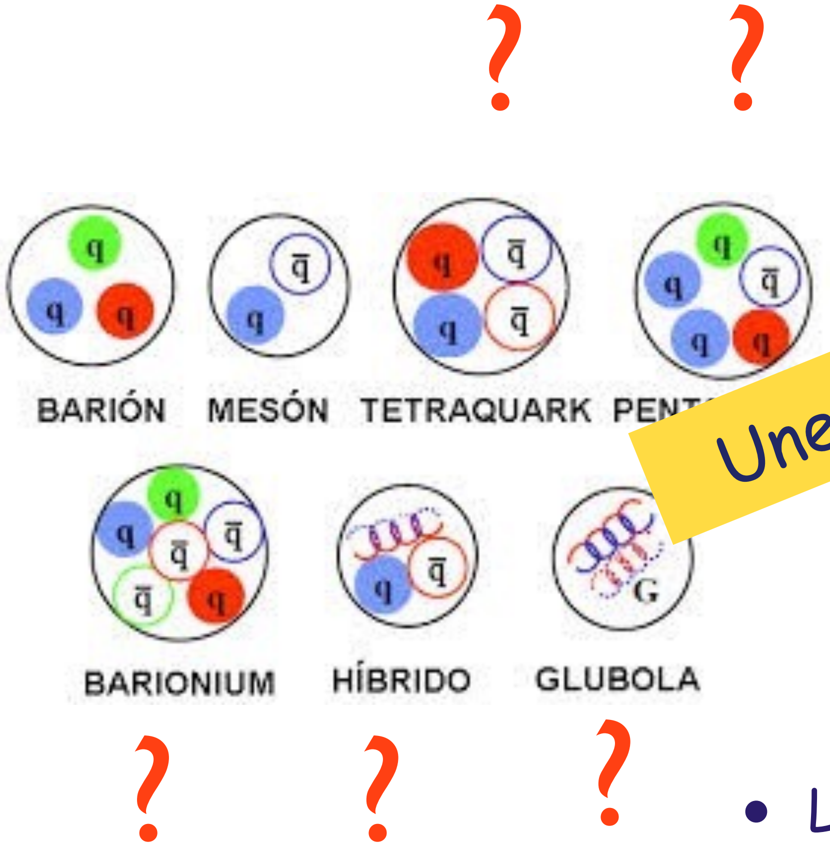

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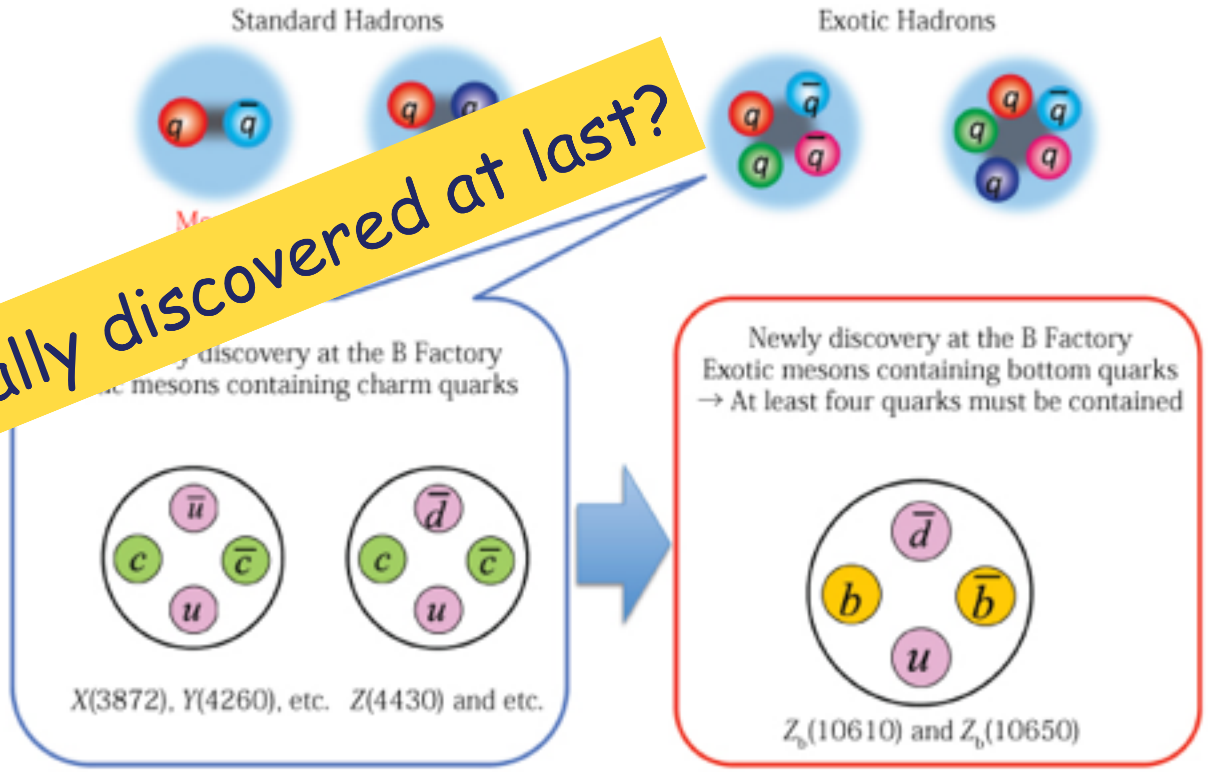
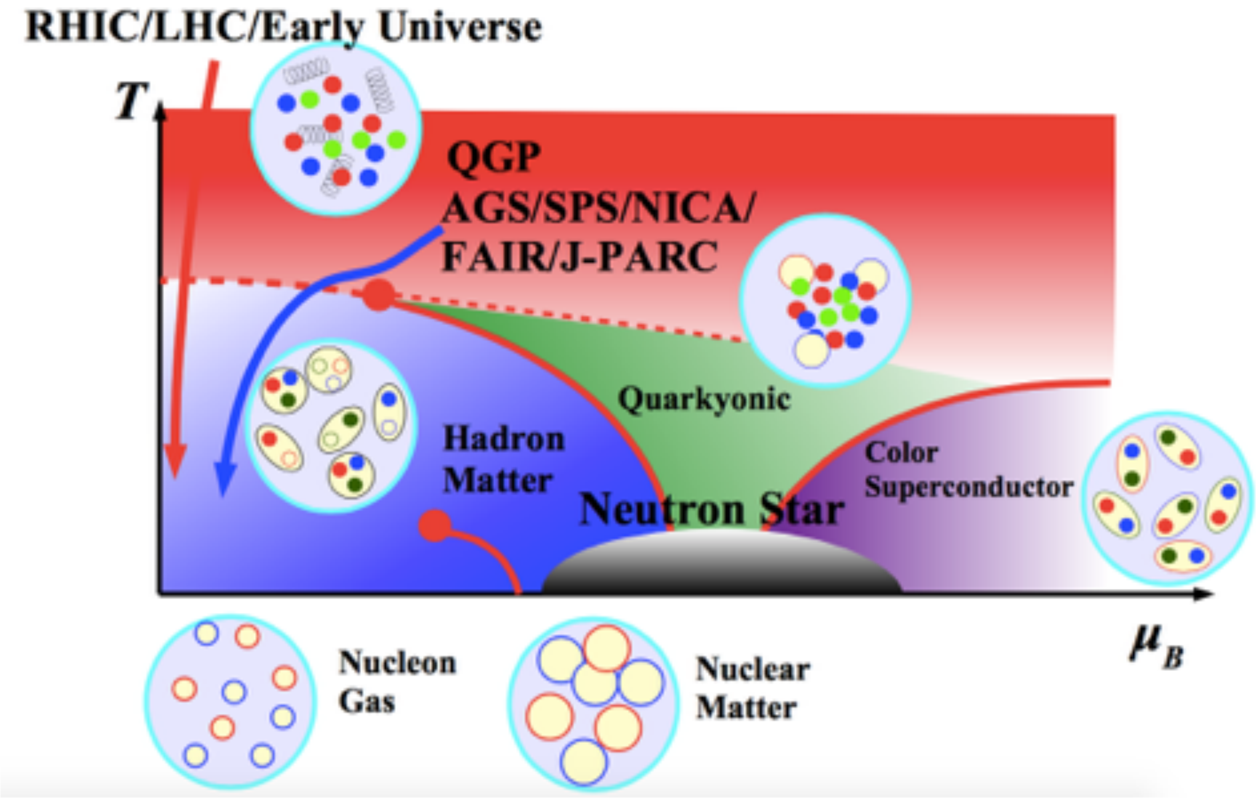


- Lattice gauge theories
- Holographic approach
- Gauge theories in dual description
- Back to analyticity & unitarity ?

Dense hadron matter - new phase?



J.C. and H. Satz, Z. fuer Physik C57, 135, 1993.

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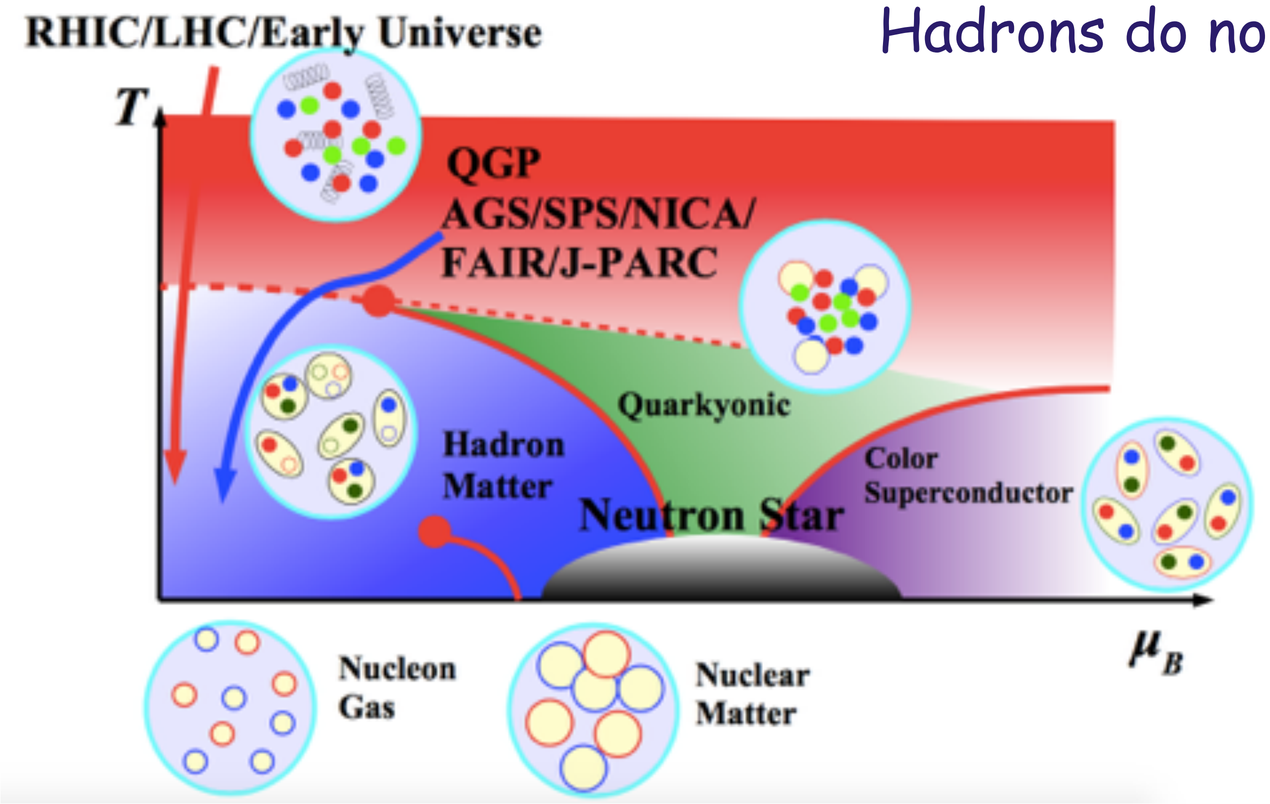

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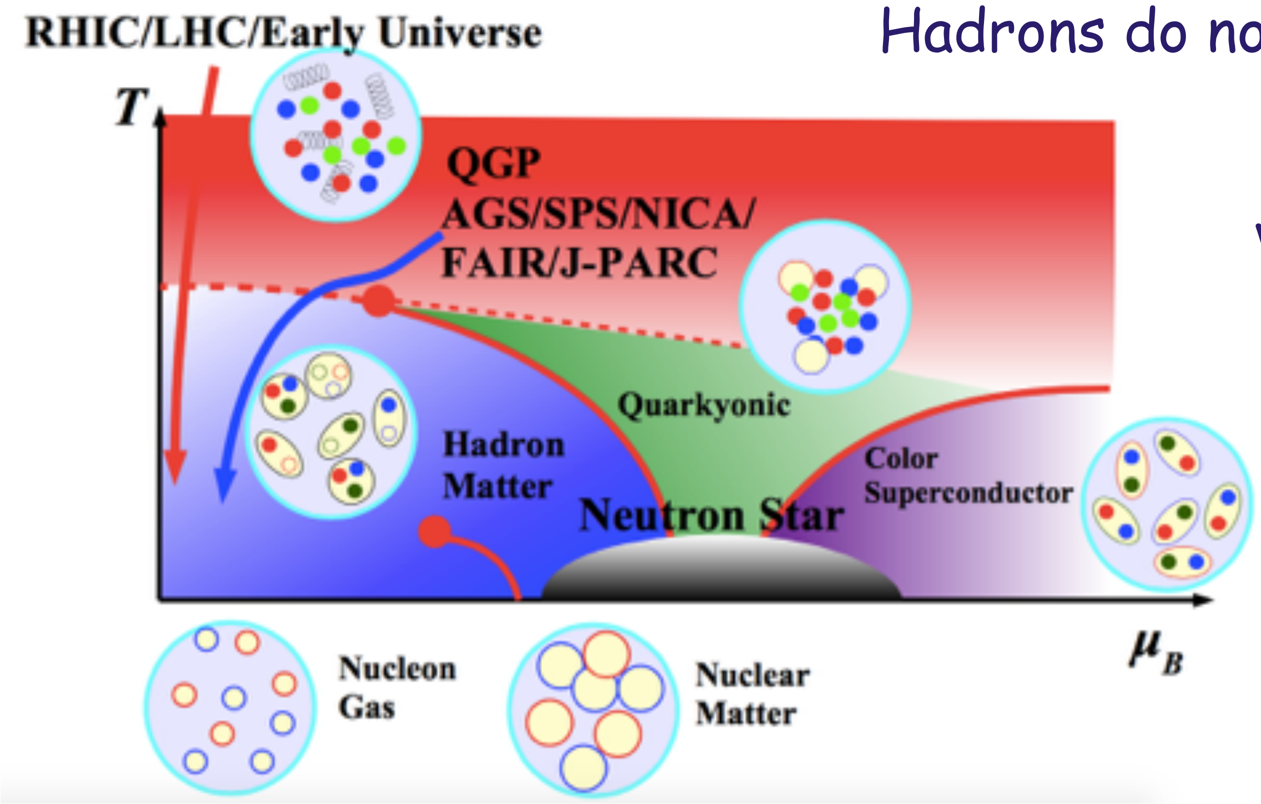

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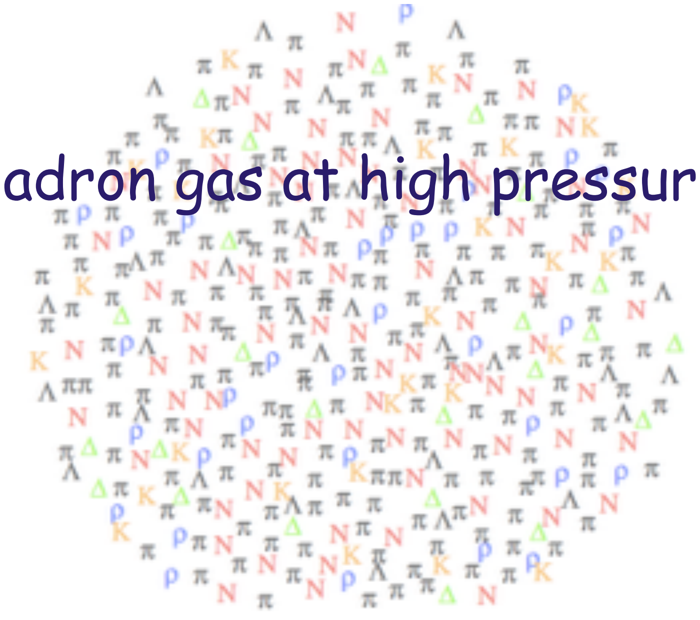

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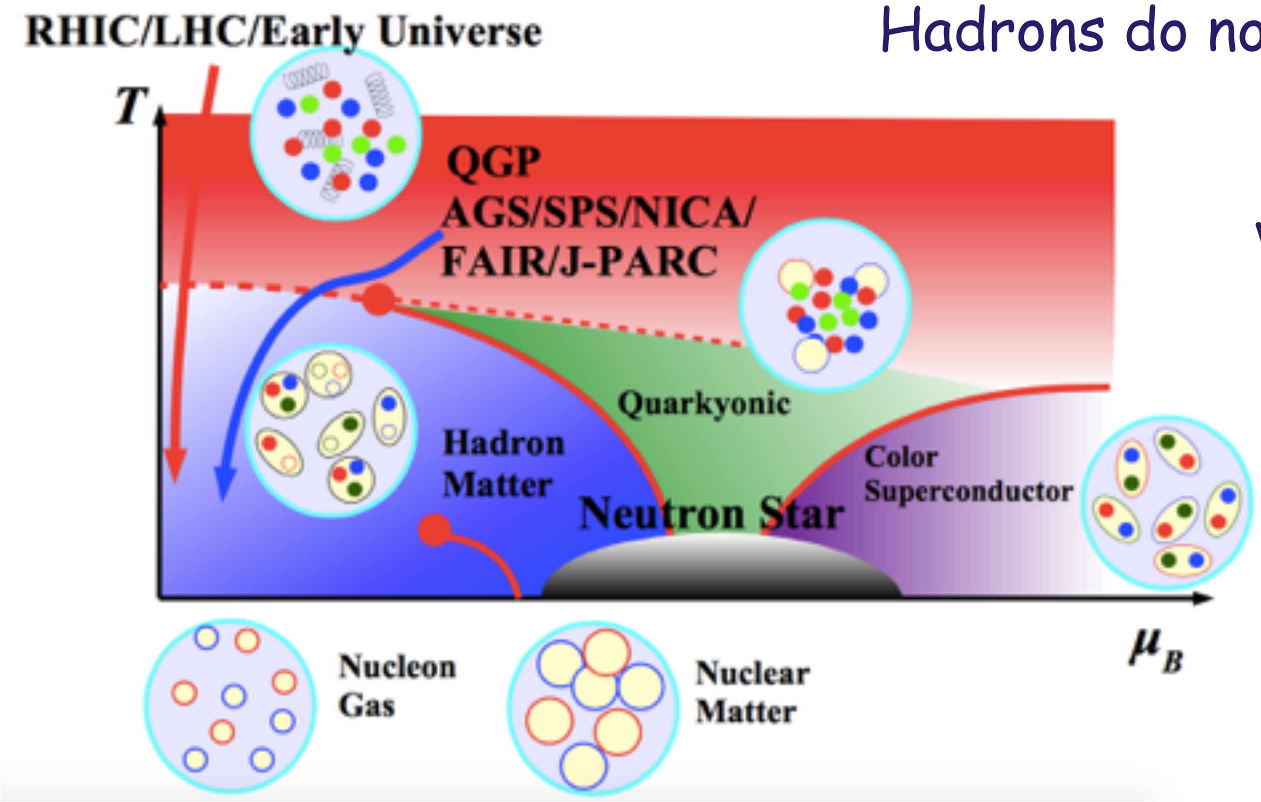

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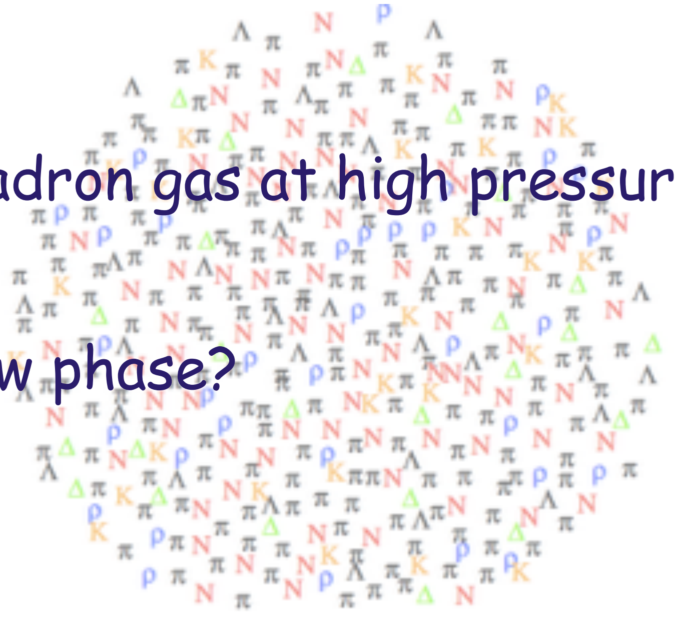

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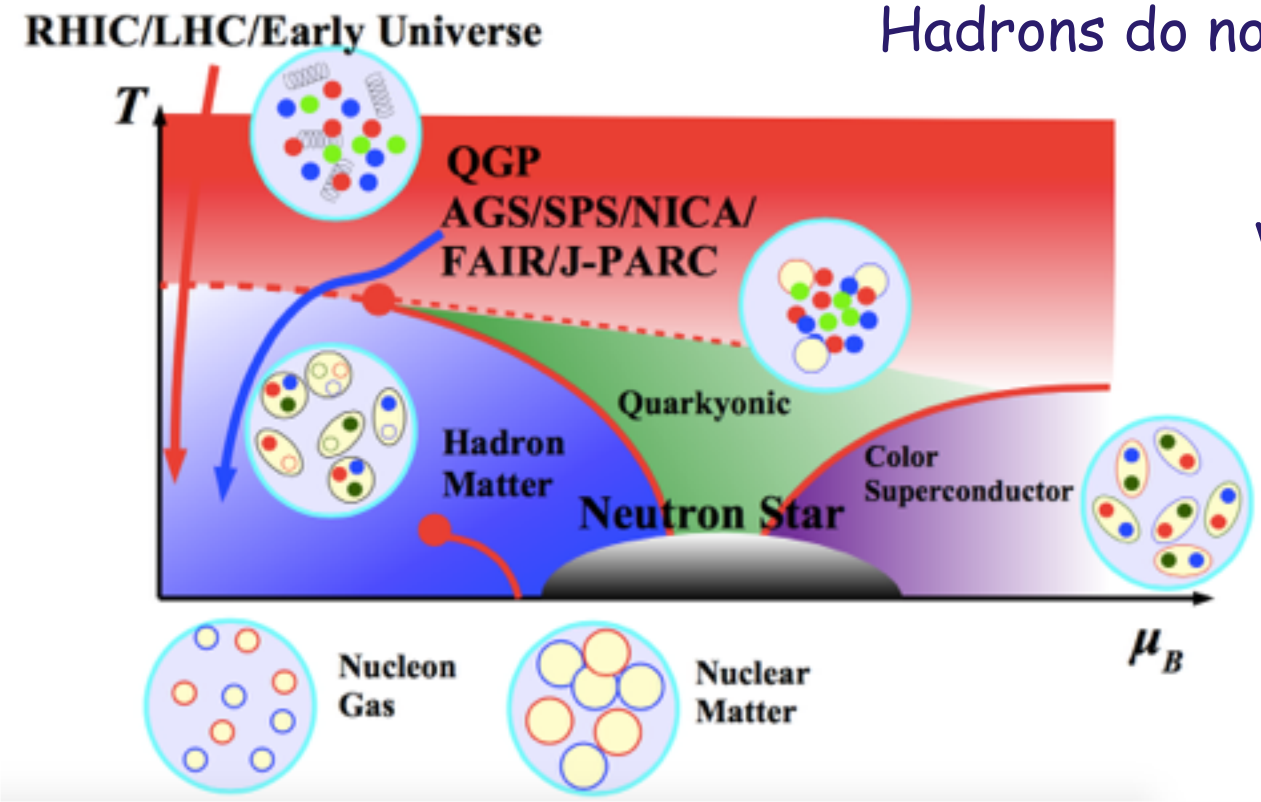

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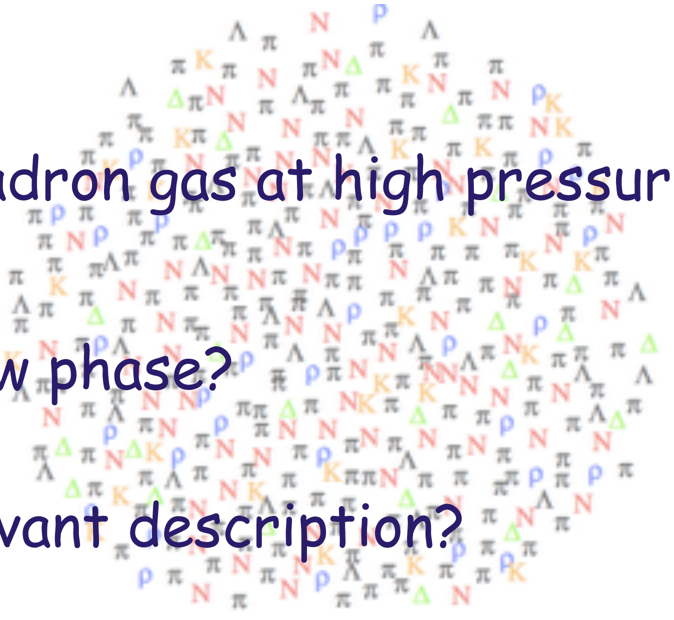

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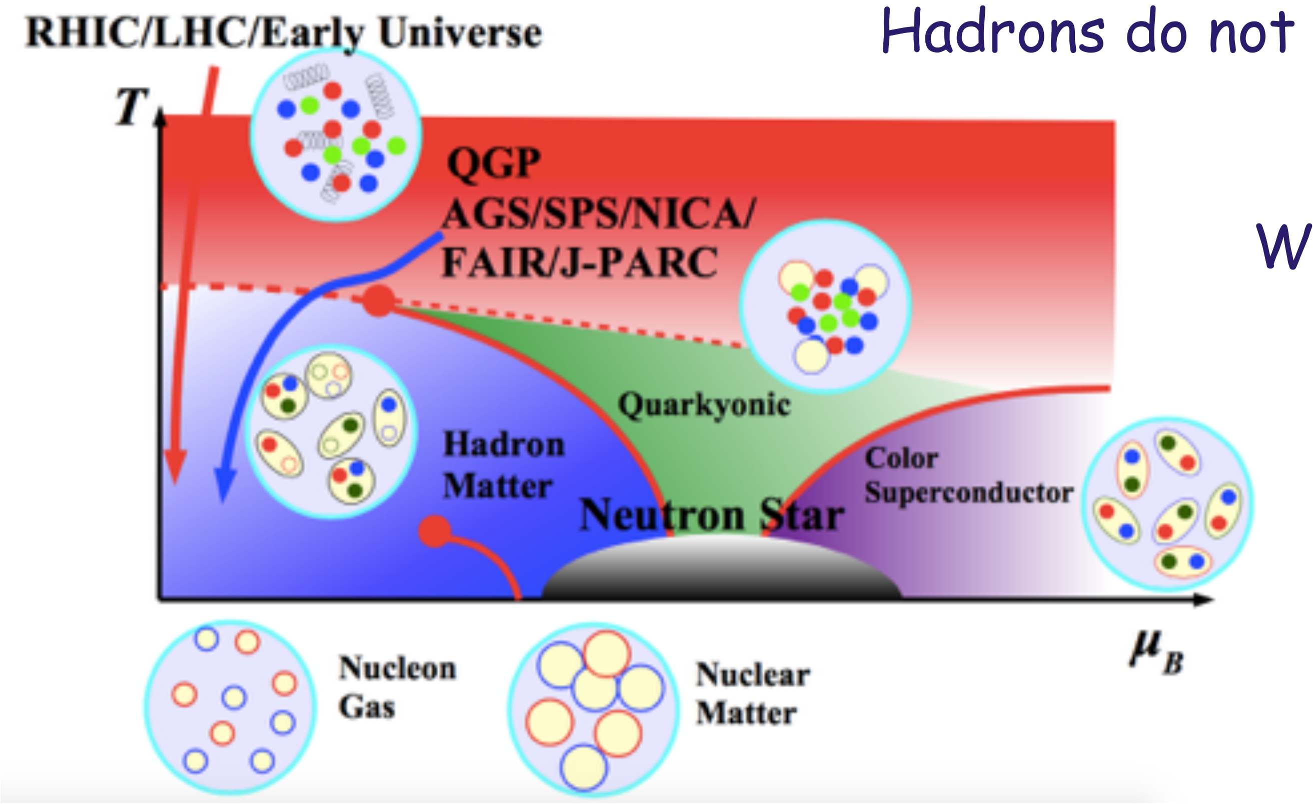

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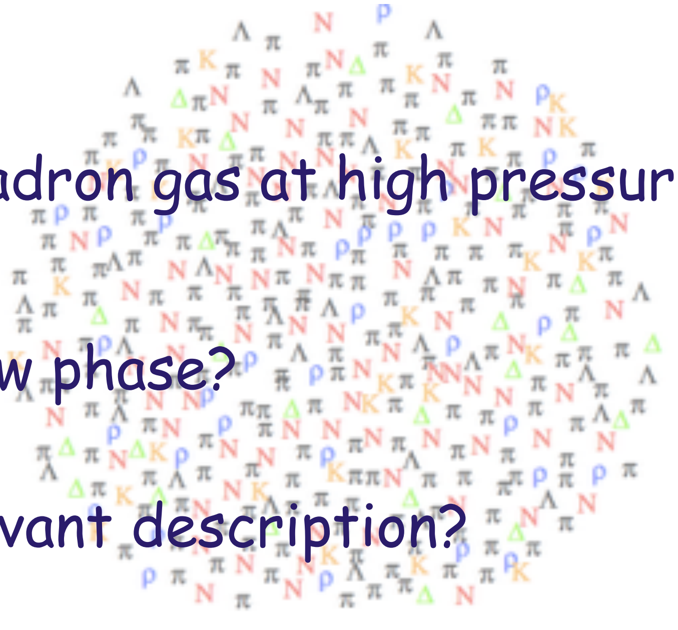

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What is the relevant description?

statistical mechanics,
nonequilibrium thermodynamics
hydrodynamics,
dual models - holography

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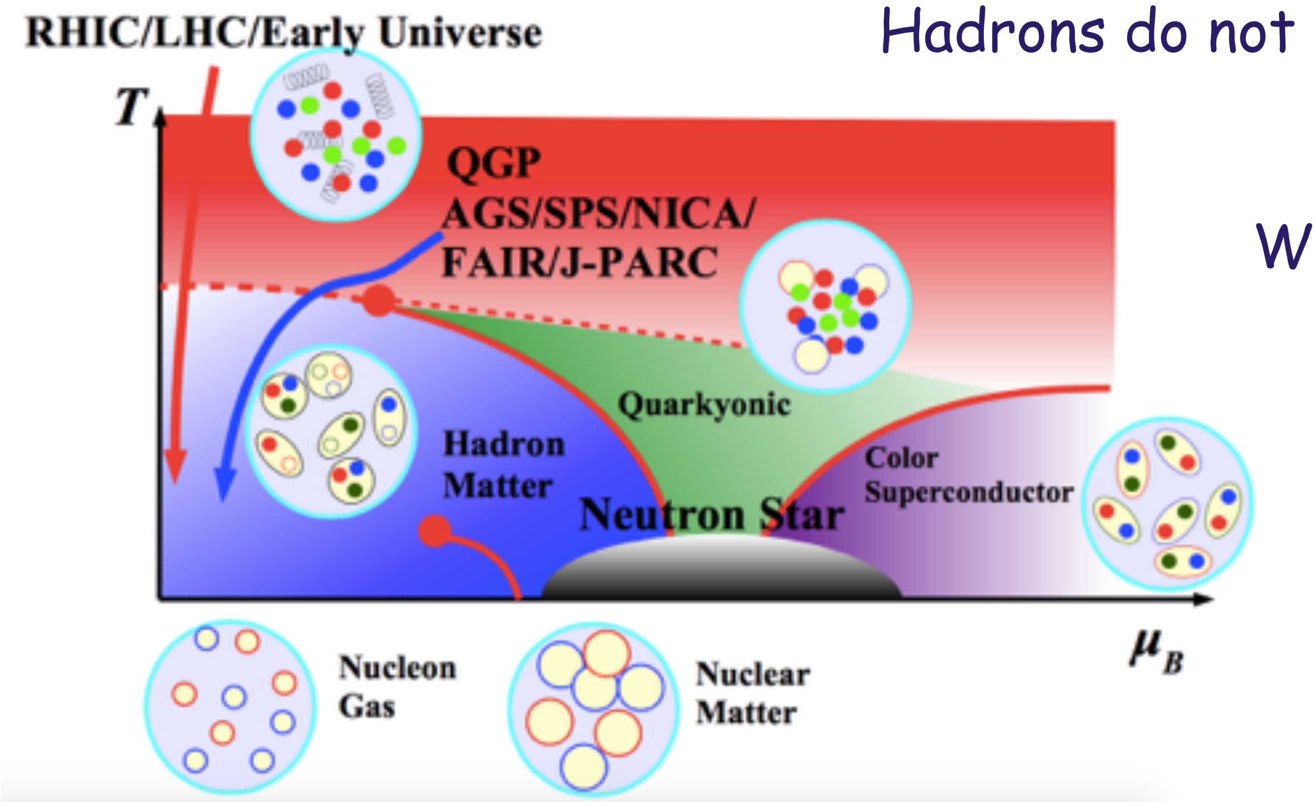

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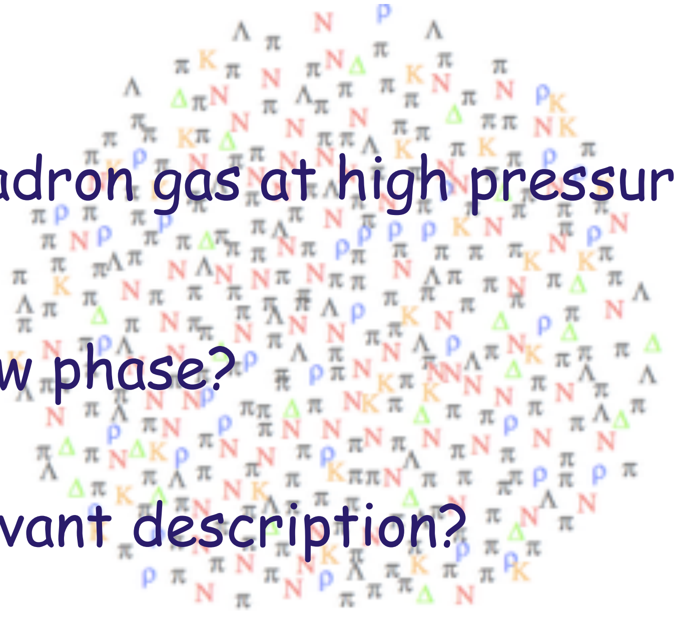

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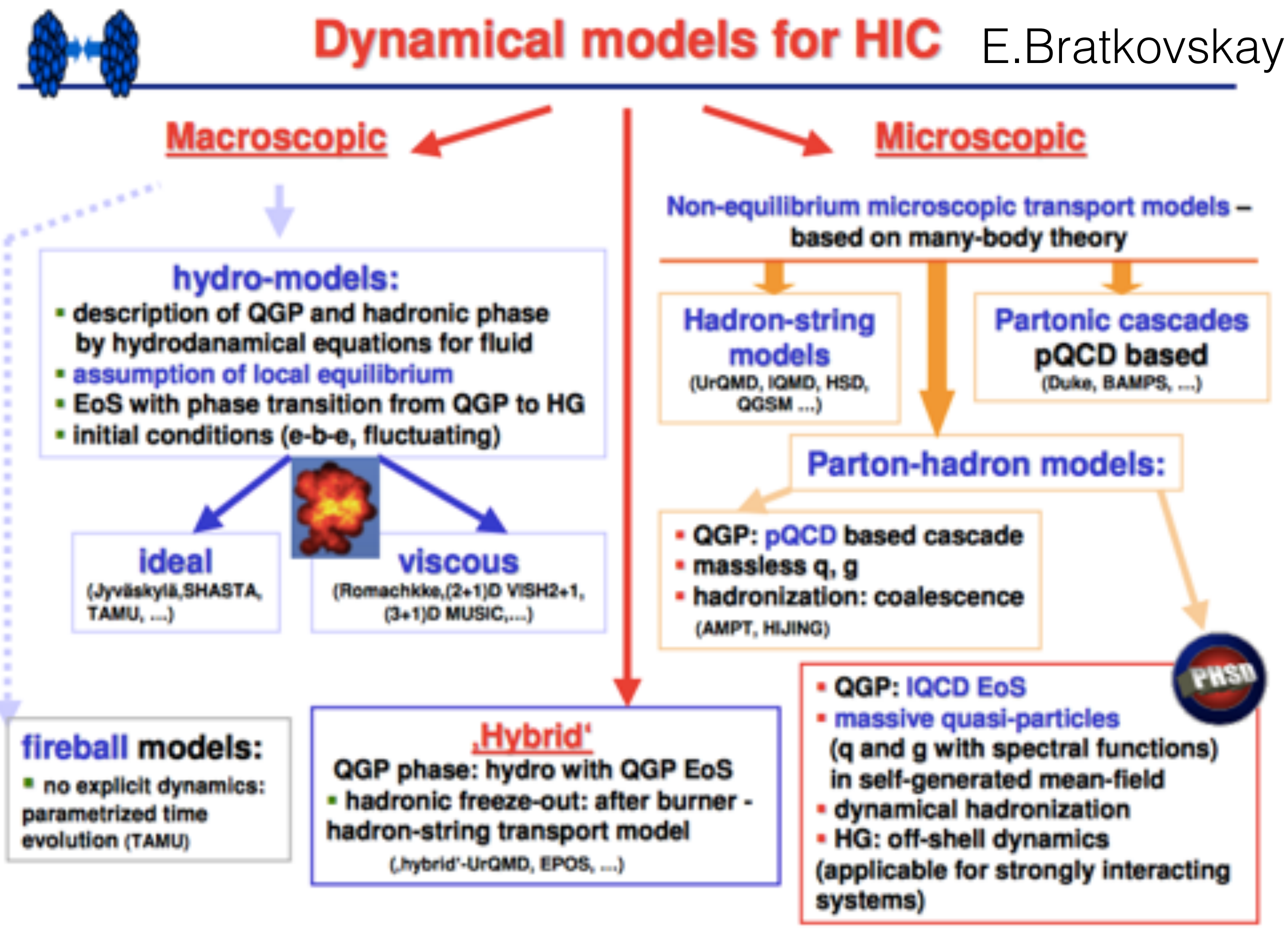

Dynamical models for HIC E.Bratkovskaya

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)

ideal (Jyväskylä,SHASTA, TAMU, ...)

viscous (Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,...)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

‚Hybrid'
QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model
(‚hybrid'-UrQMD, EPOS, ...)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models (UrQMD, IQMD, HSD, QGSM ...)

Partonic cascades pQCD based (Duke, BAMPS, ...)

Parton-hadron models:

- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

PHSD
- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
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(applicable for strongly interacting systems)

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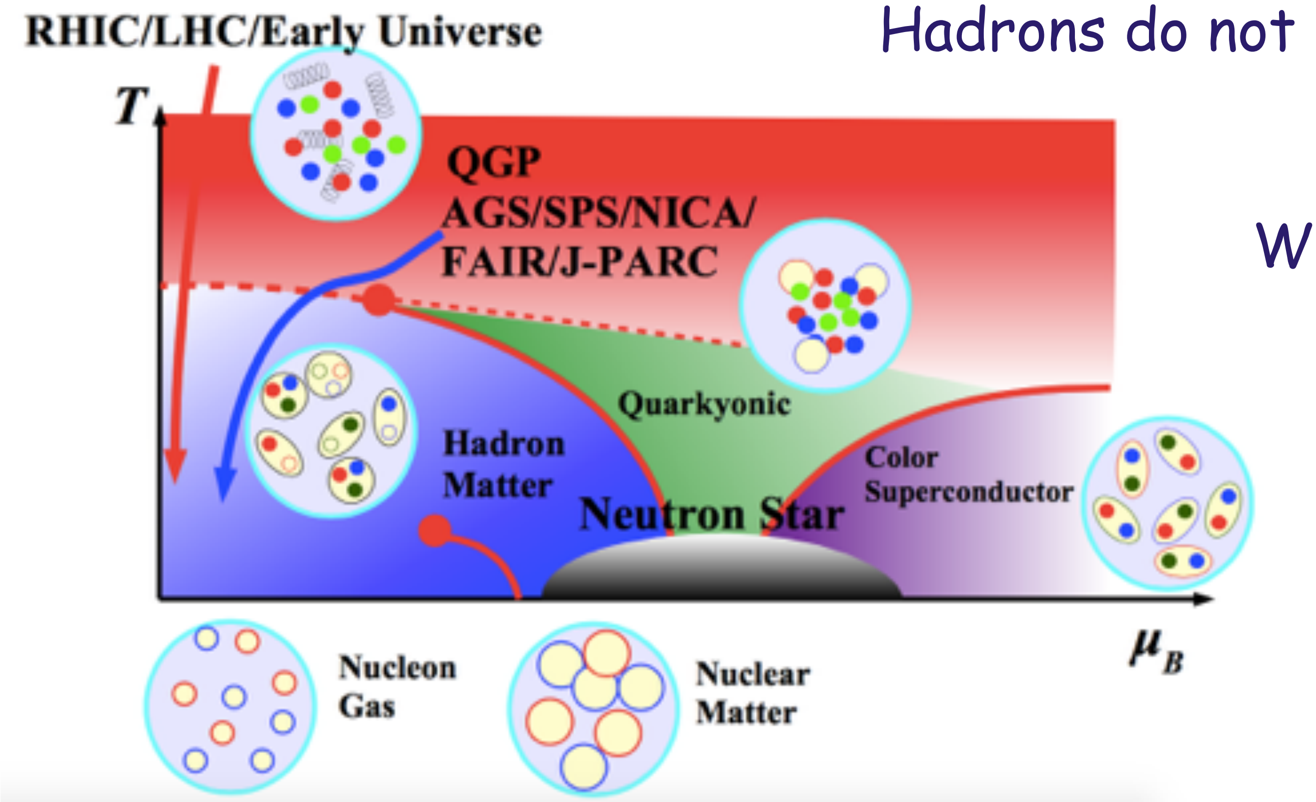

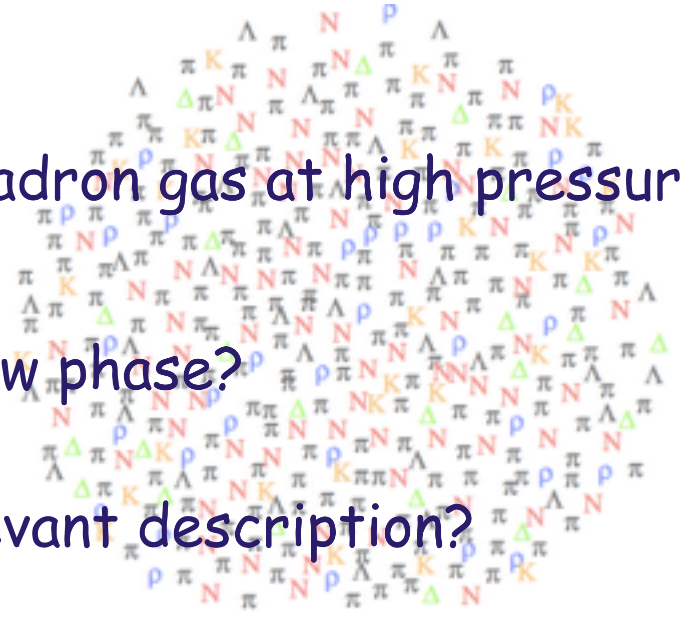

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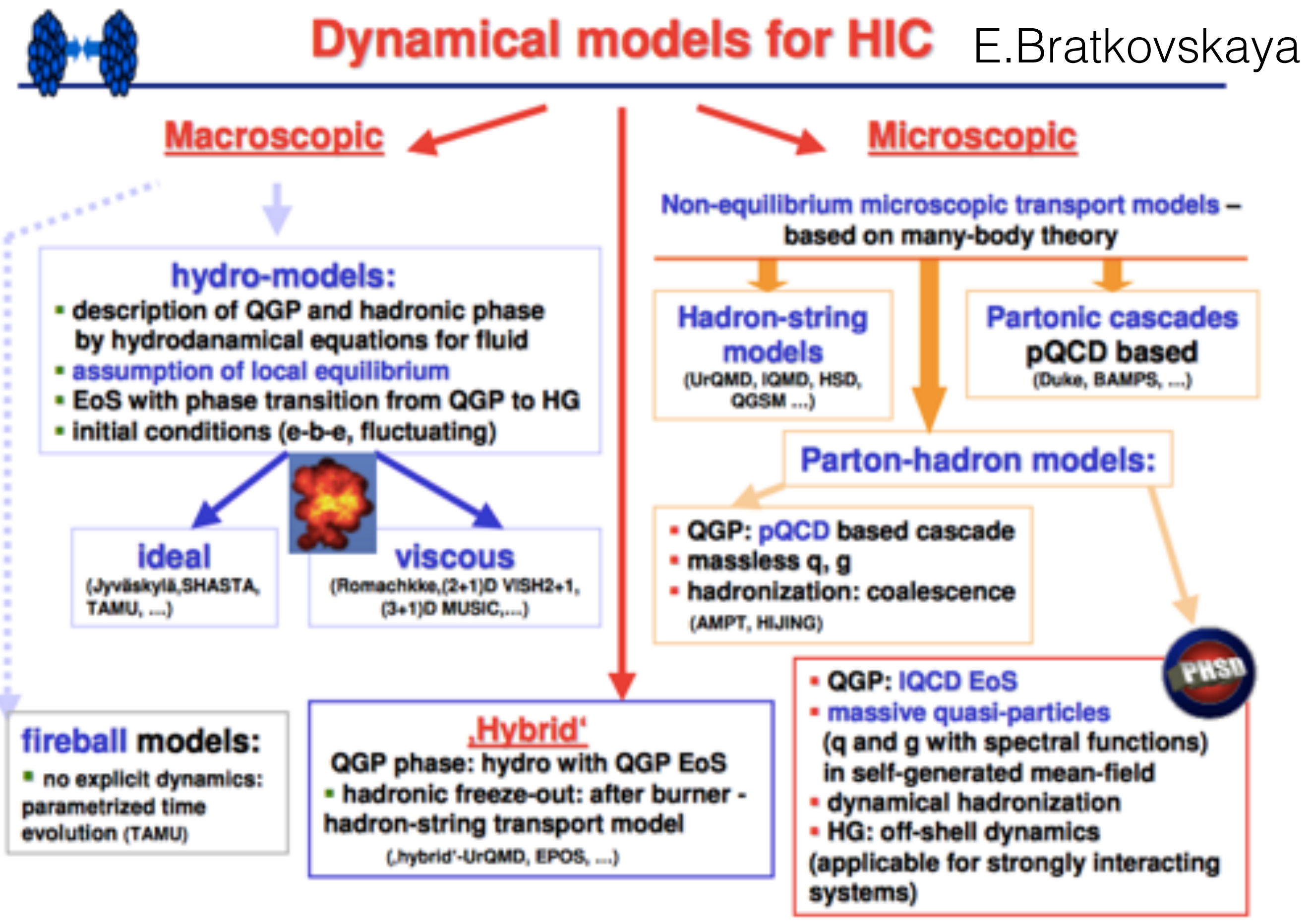

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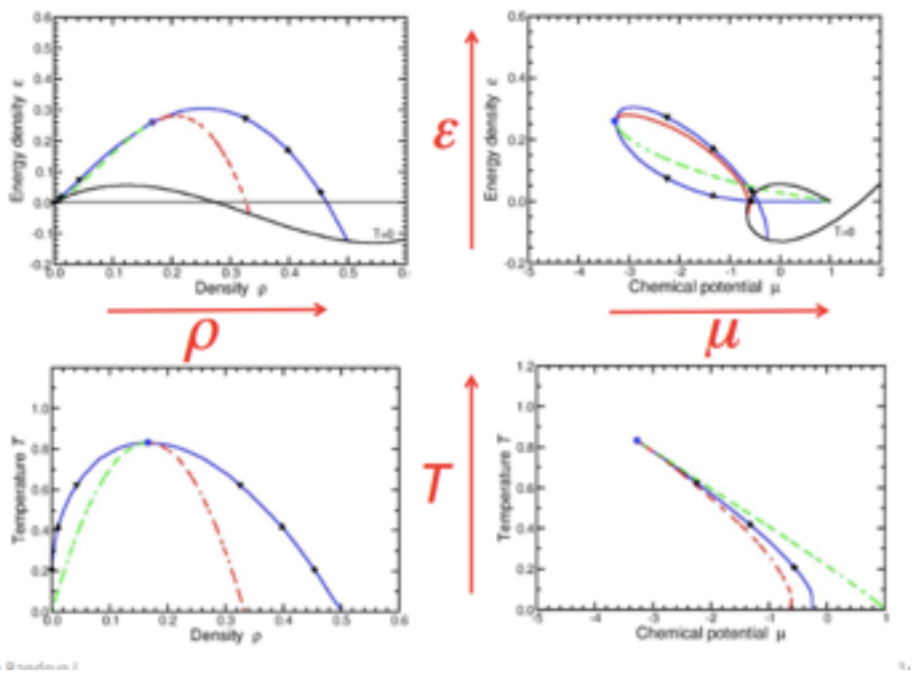
Nuclear phase diagram in different representations



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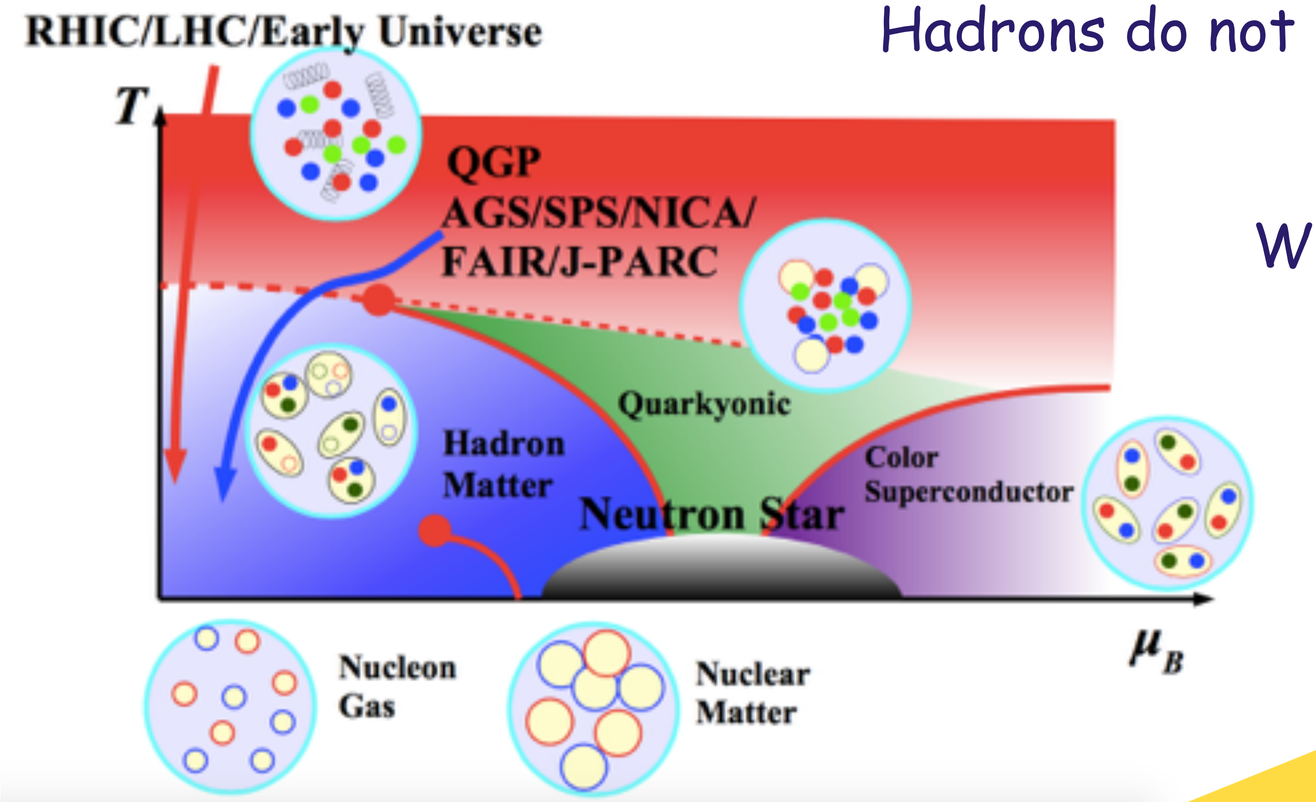

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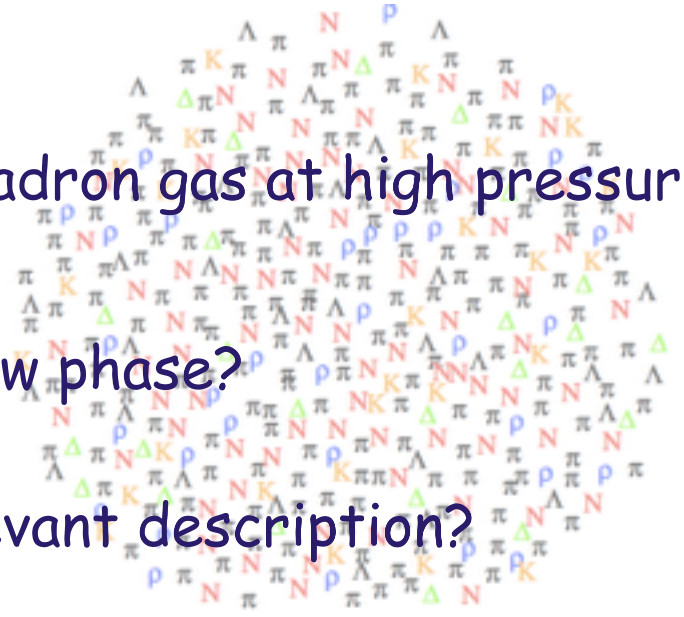

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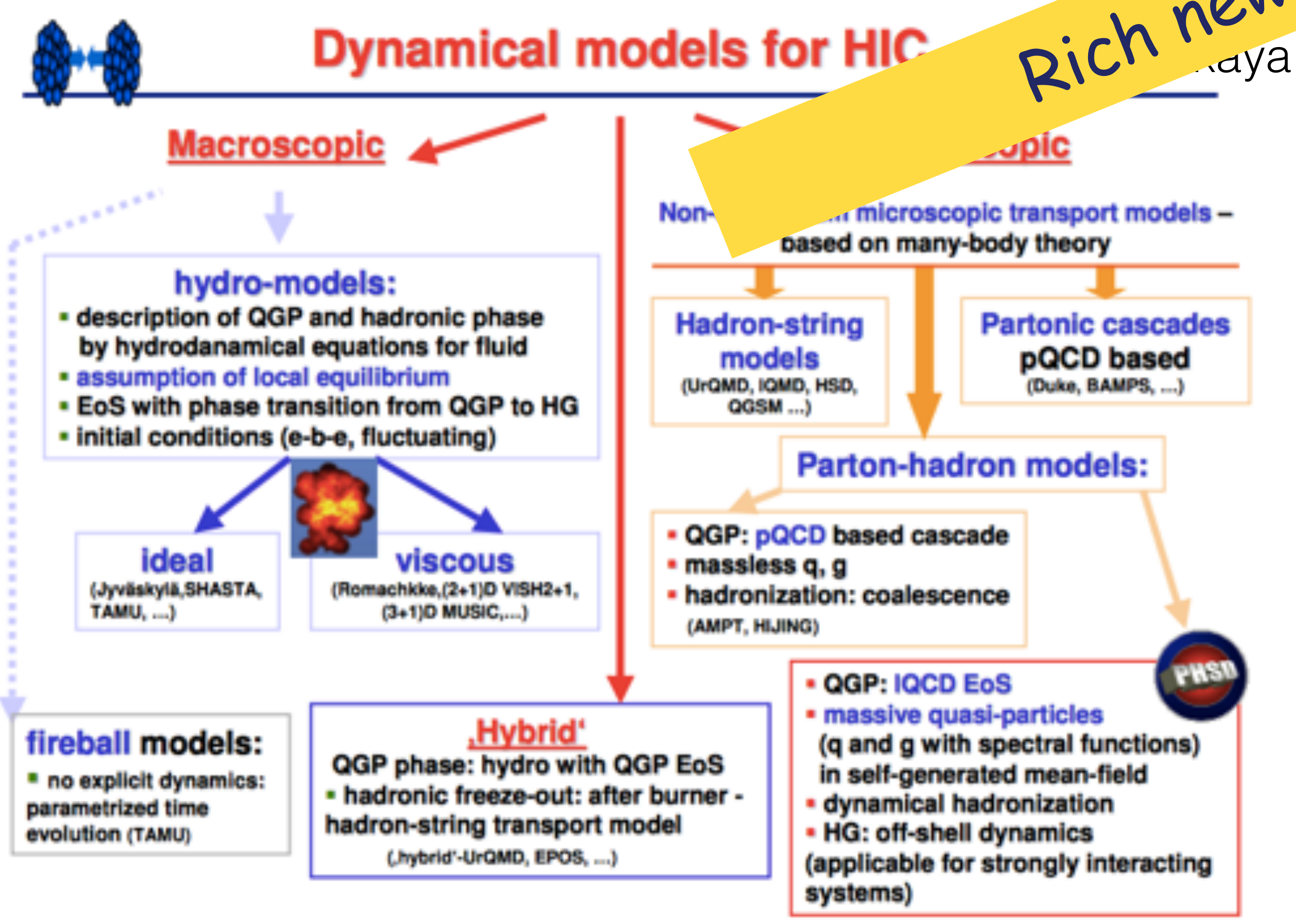

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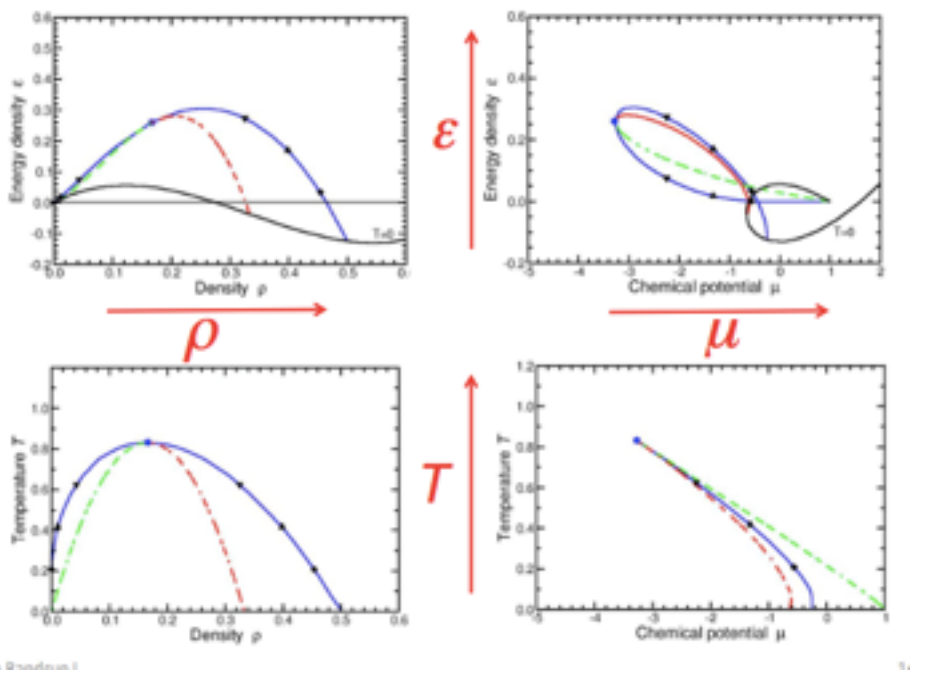
Nuclear phase diagram in different representations



Search for New Physics

The Higgs Boson - Target # 1

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Is it the SM Higgs boson or not?

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Custodial symmetry as guiding principle for extensions

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

indicates that an approximate global symmetry exists,

broken by the vev to the diagonal ‘custodial’ symmetry

group $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$

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Thus the Higgs field transforms under $SU(2)_L \times SU(2)_R : \quad \Phi \rightarrow L\Phi R^\dagger$

$$\rho = \frac{\sum\limits_{i=1}^{n}[I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum\limits_{i=1}^{n}\frac{1}{2}Y_i^2 v_i} \sim 1$$

For both SU(2)-singlet with Y=0

and SU(2) doublet with Y=+-1

M.Spannowsky

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Any number of singlets and doublets respects custodial symmetry at tree level. Not so for arbitrary triplet models …

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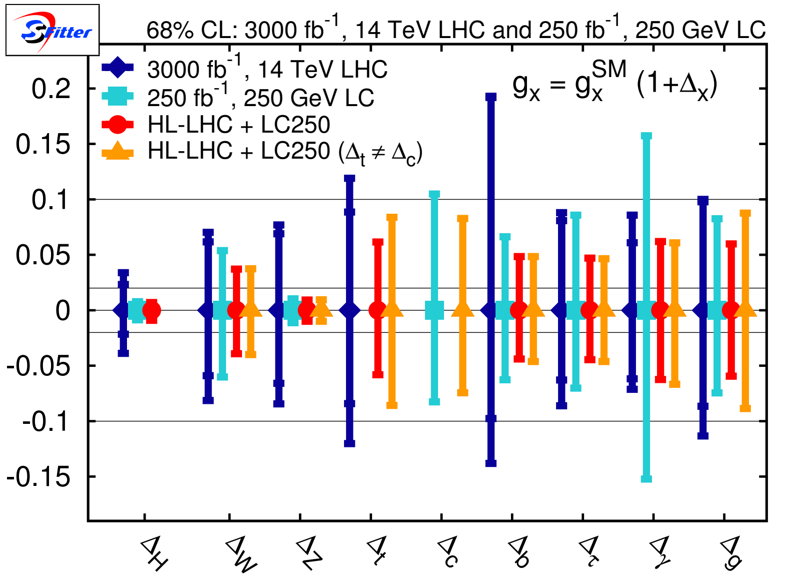

[Klute, Lafaye, Plehn, Rauch, Zerwas `13]

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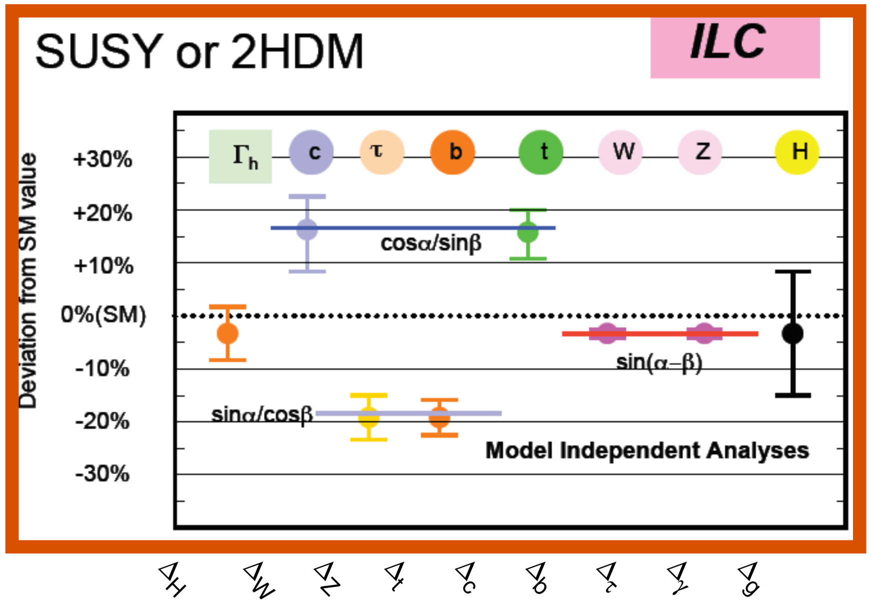

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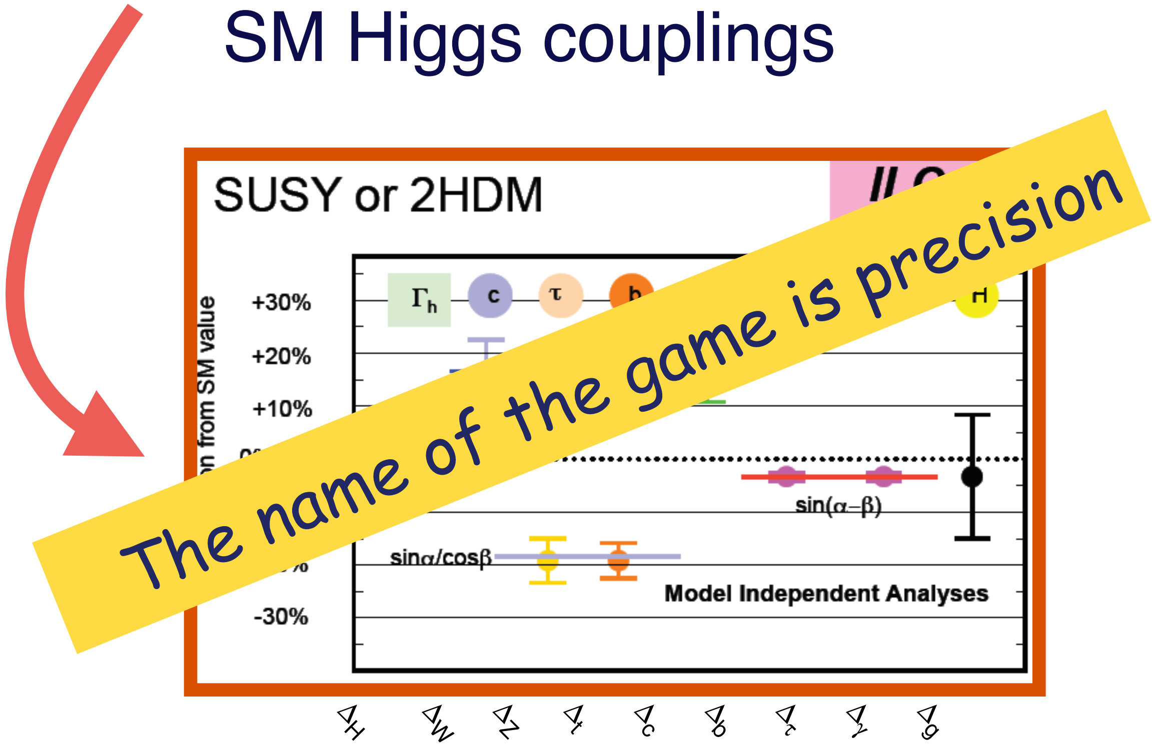

The name of the game is precision

[Klute, Lafaye, Plehn, Rauch, Zerwas `13]

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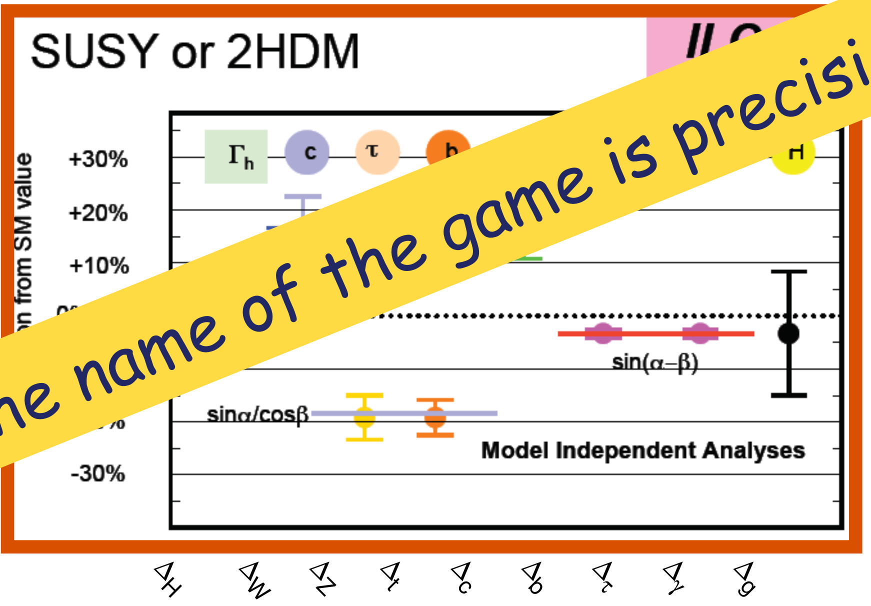

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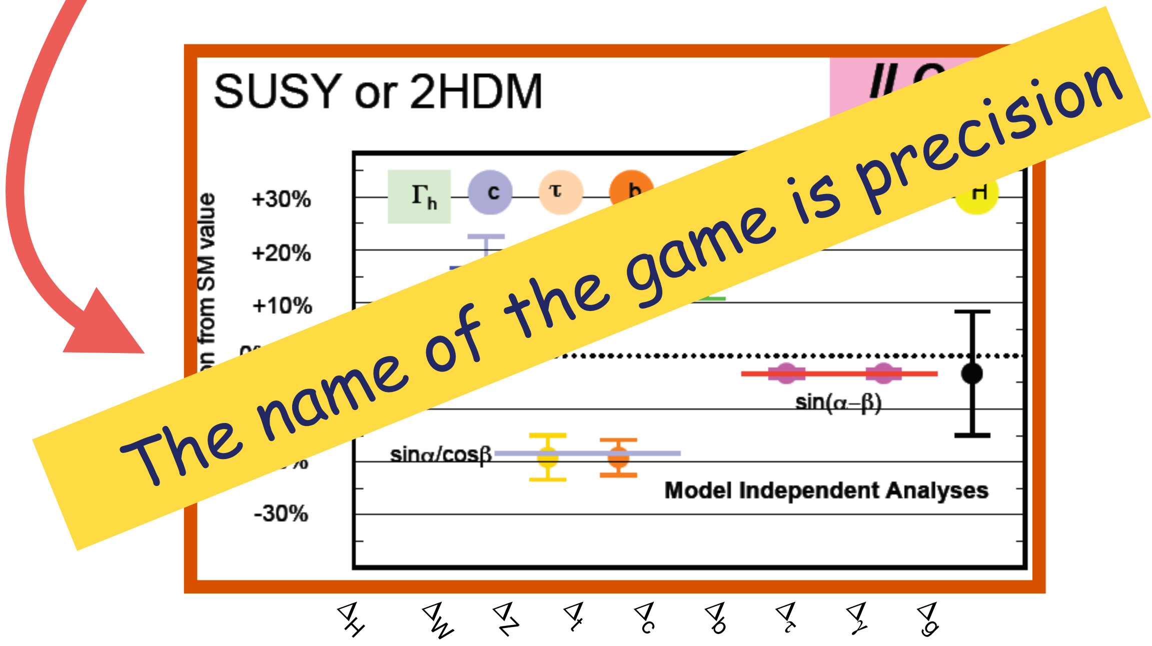

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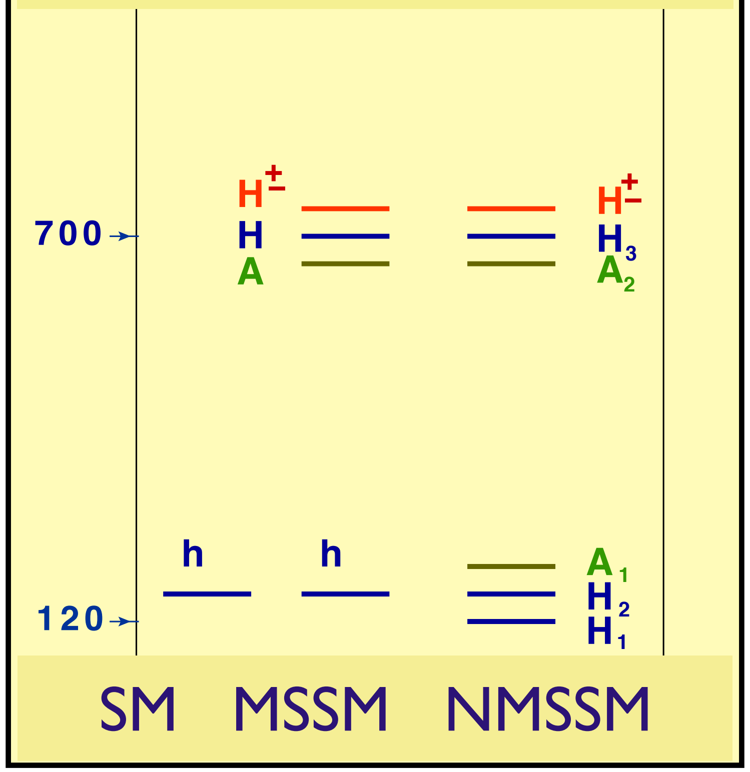
The mass spectrum of the Higgs bosons (GeV)



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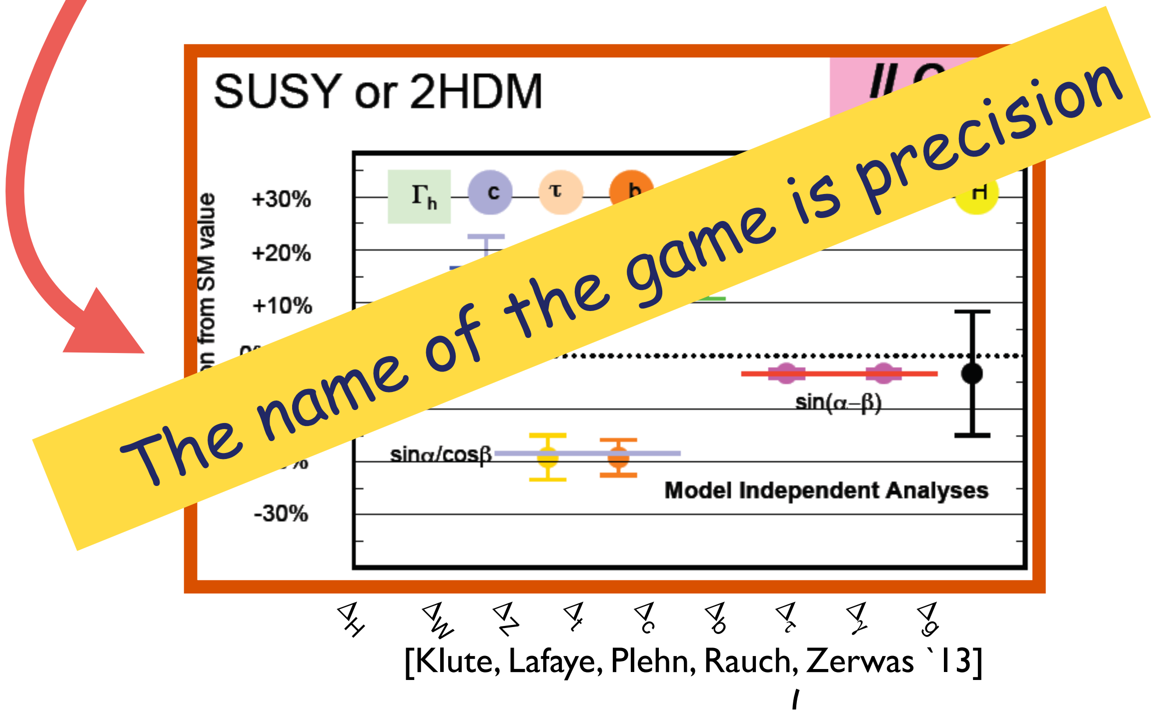

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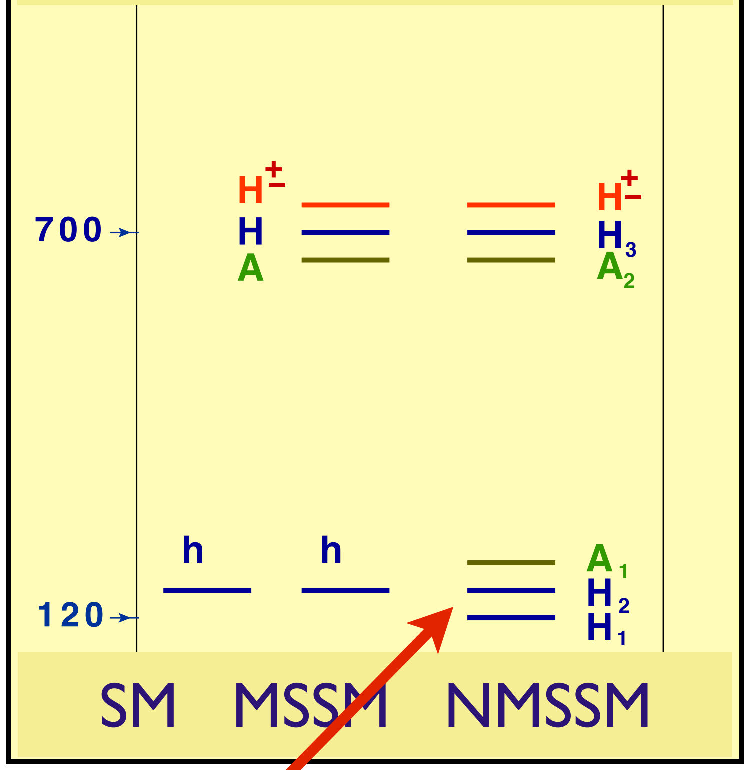

We may have found one of these states

Search for New Physics

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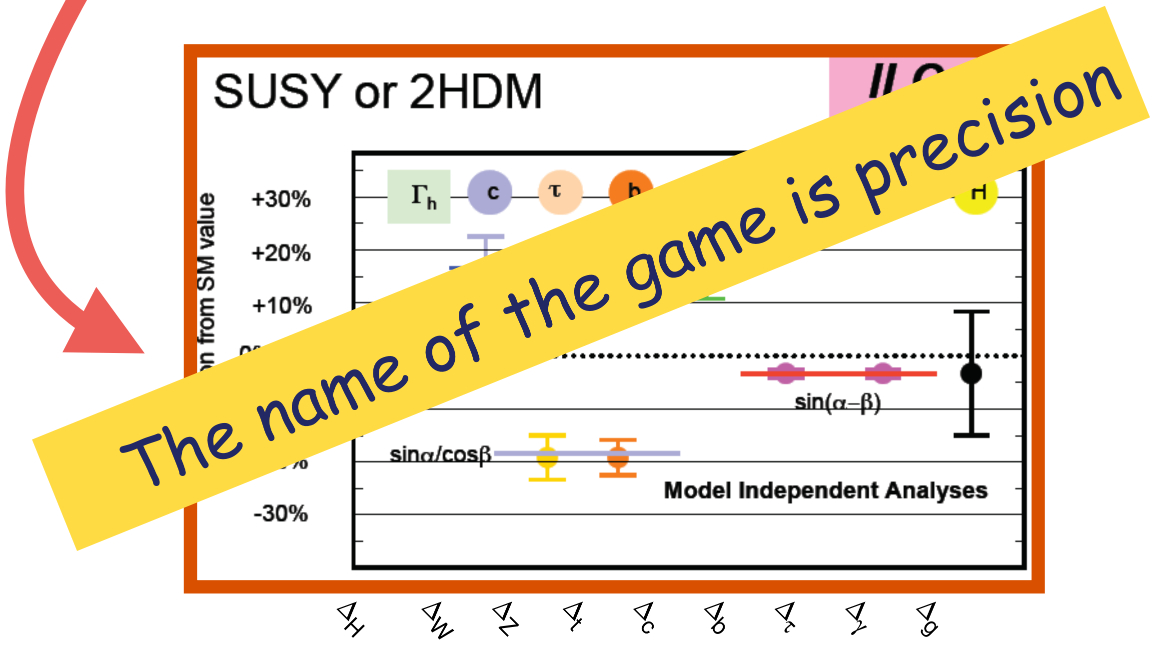

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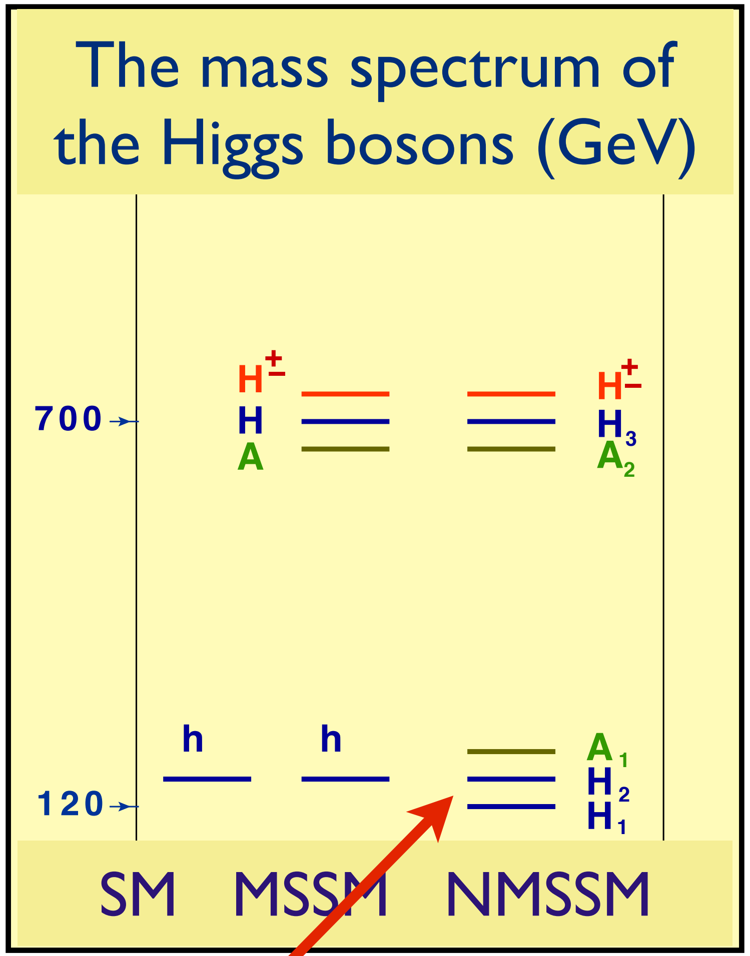
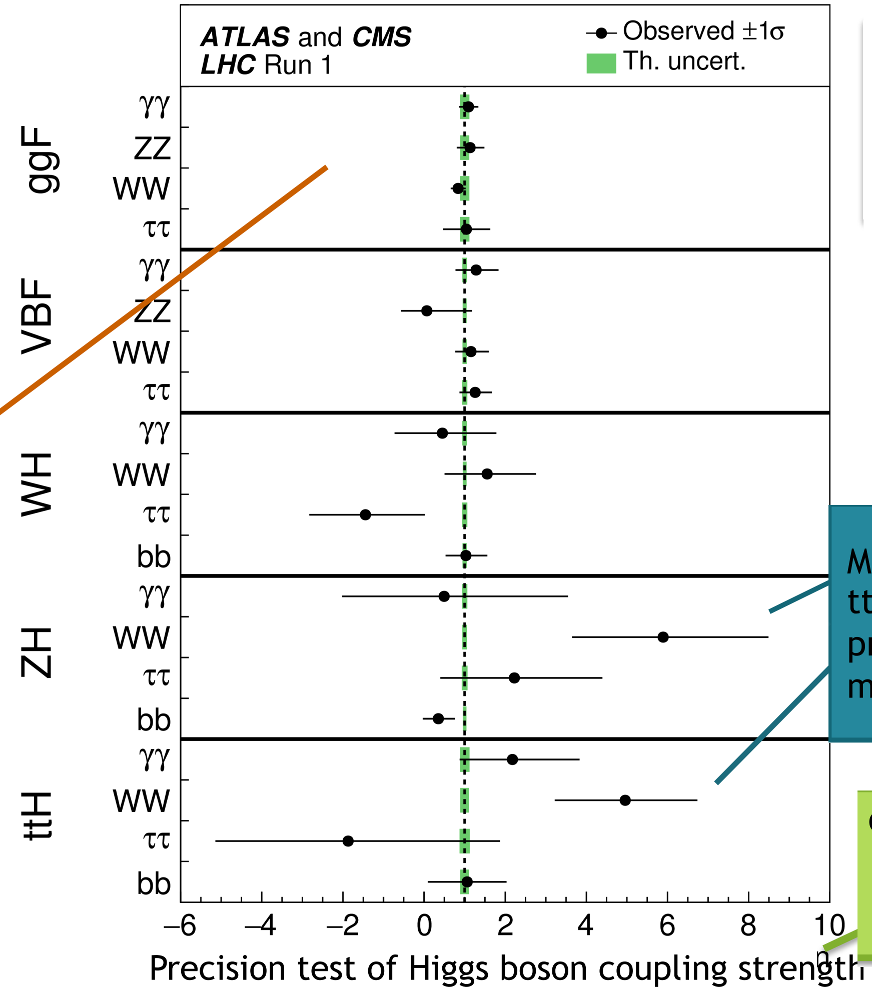

The mass spectrum of the Higgs bosons (GeV)

We may have found one of these states

- The Higgs physics has already started
- This is the task of vital importance.
- May require the electron-positron collider

Higgs Boson (125)



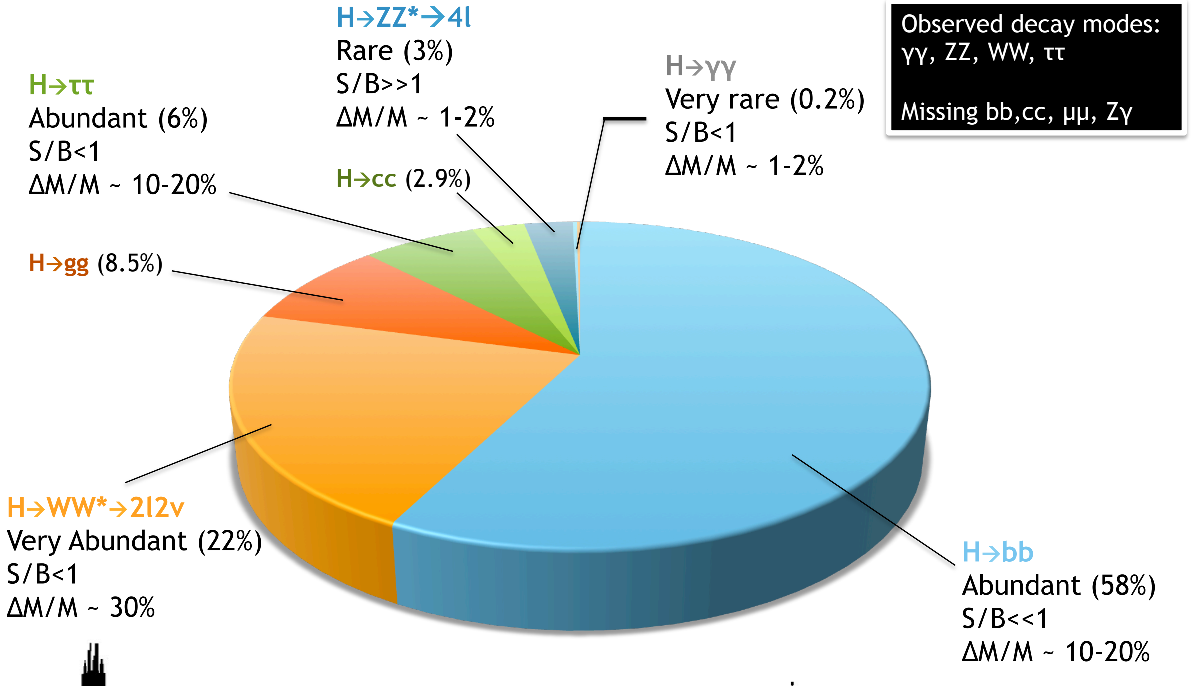
Gluon fusion measurements, starting to approach SM theory uncertainties: **15%**

Mild excess in ttH and ZH production modes

Coupling strengths

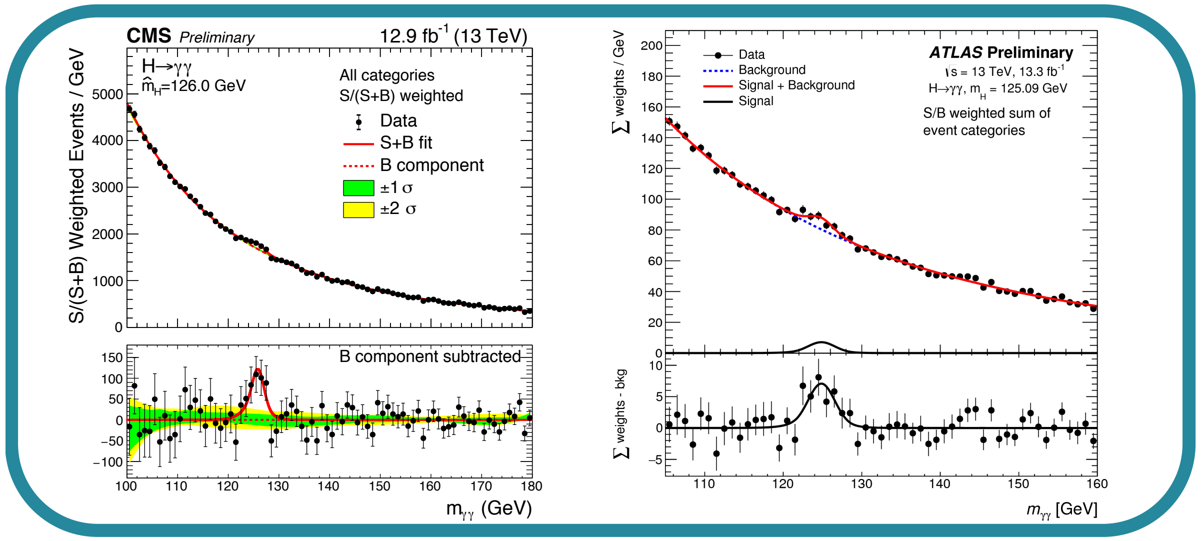
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

- Mass has been measured to 0.2% precision
  m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

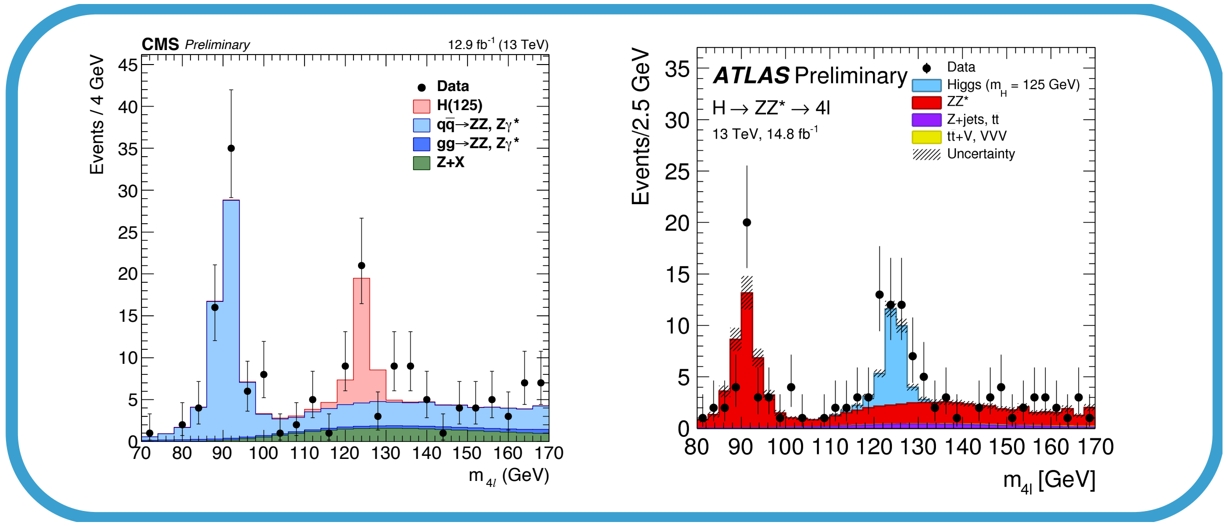


Observed decay modes:
γγ, ZZ, WW, ττ

Missing bb,cc, μμ, Zγ



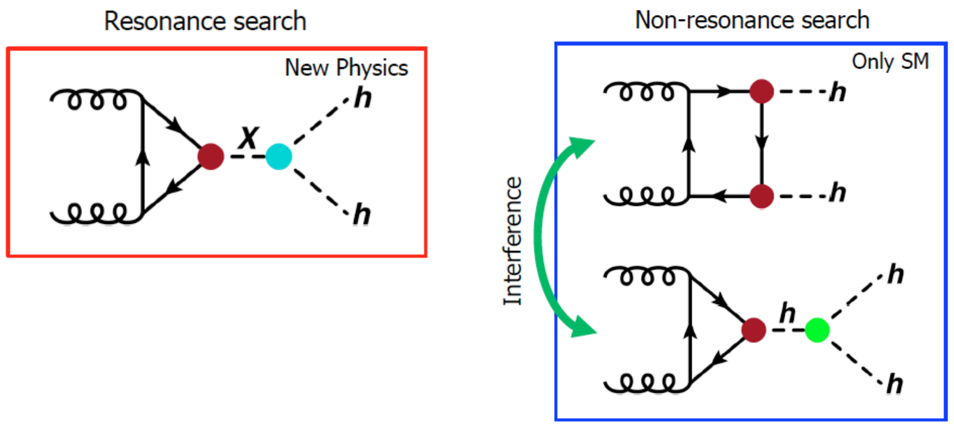
Higgs→γγ



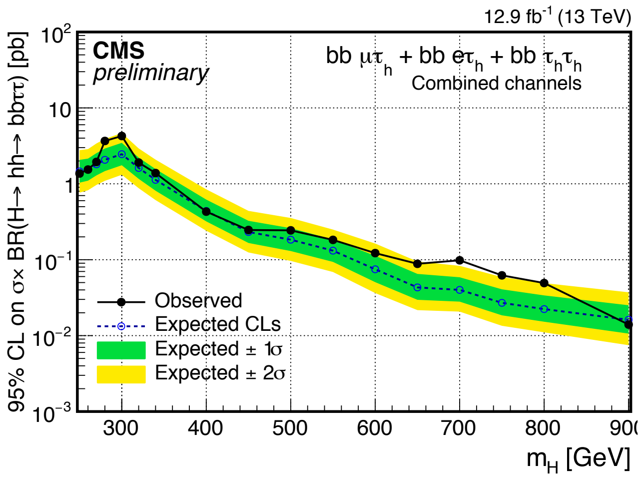
Higgs→ZZ*

Extra Higgs Bosons

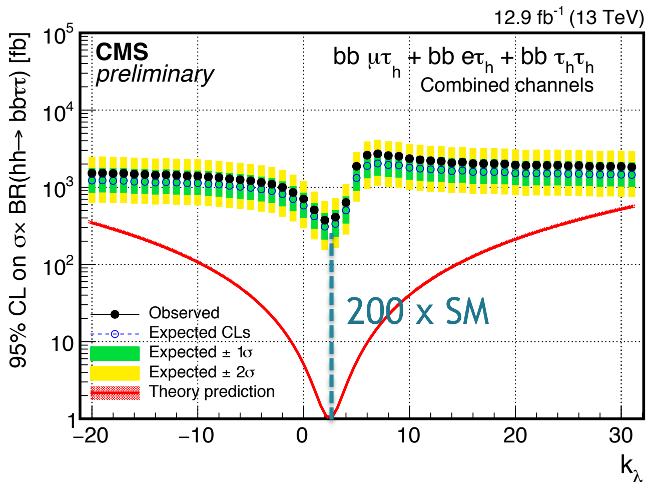
Higgs→hh→bbττ



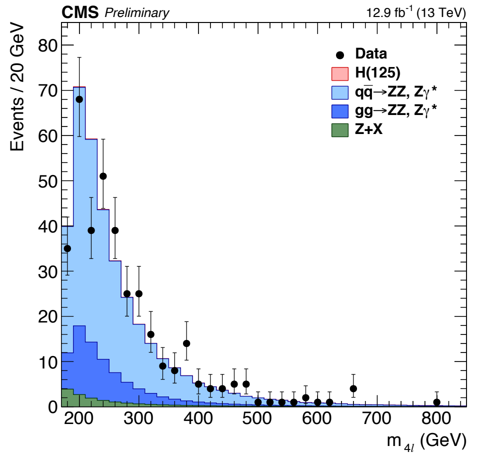
Resonant

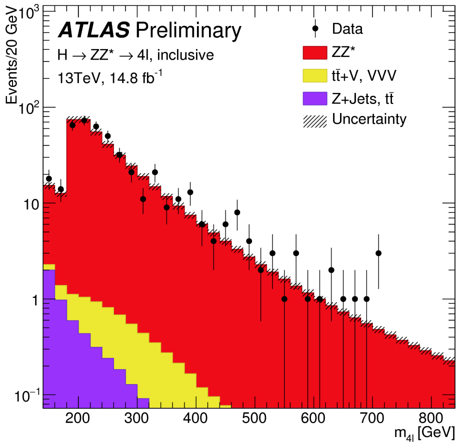


Non-Resonant

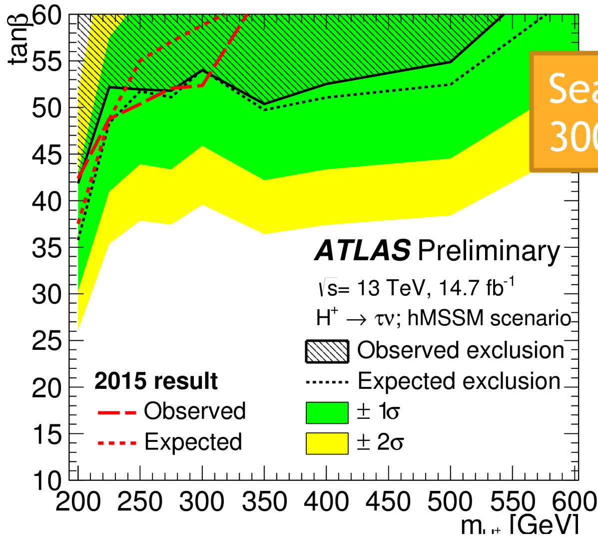


Heavy Higgs→ZZ→4l



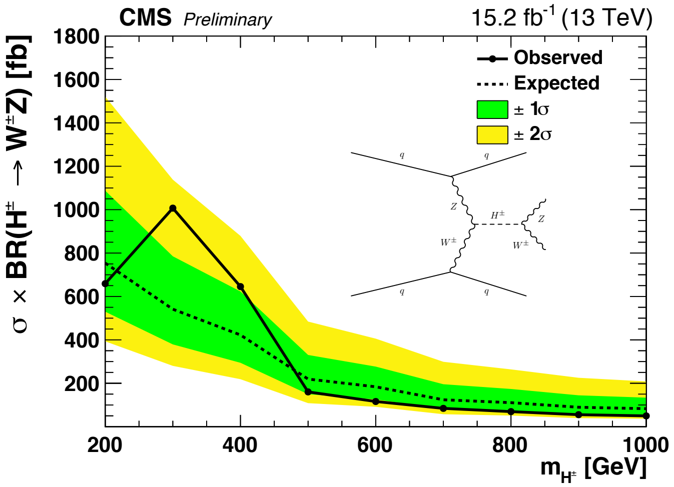


Charged Higgs

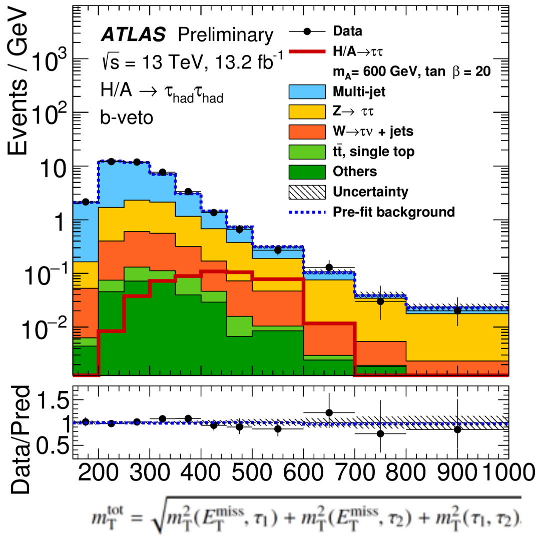


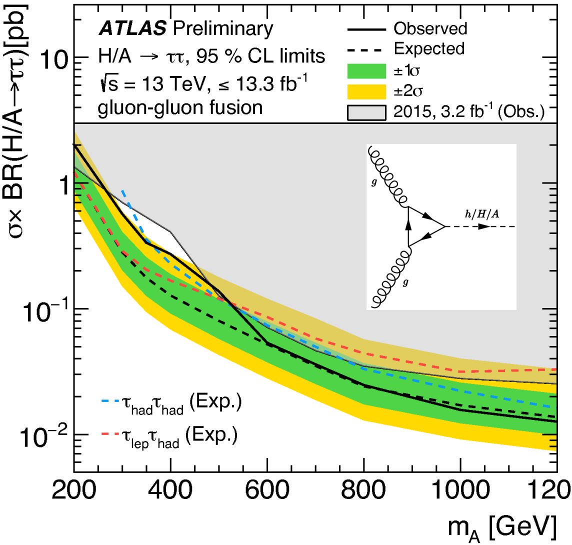
Search for H±→tb
300<m$_{H^±}$<1000 GeV

Search for H±WZ



Heavy Higgs→ττ





Search for New Physics

The Dark Matter - Target # 2

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino
  - axion (axino)
  - neutralino
  - sneutrino
  - gravitino
  - heavy photon
  - heavy pseudo-goldstone
  - light sterile higgs

mSUGRA

Not from the SM

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WIMP

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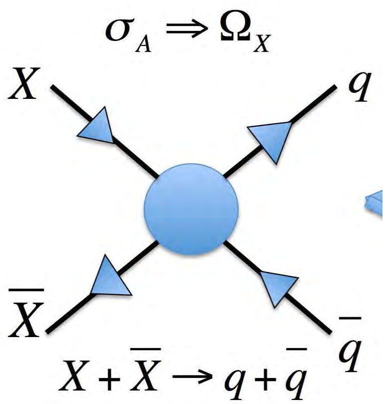
Annihilation in the halo

WIMP



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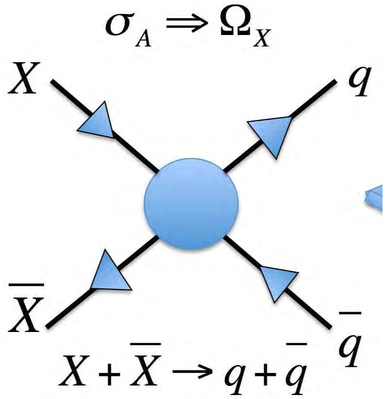
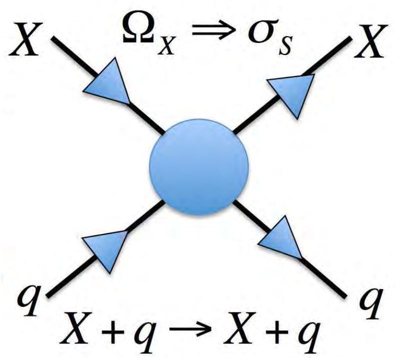


Scattering on a target



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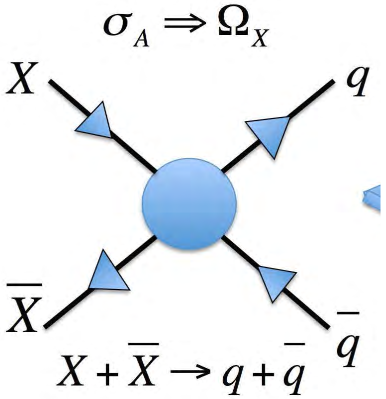

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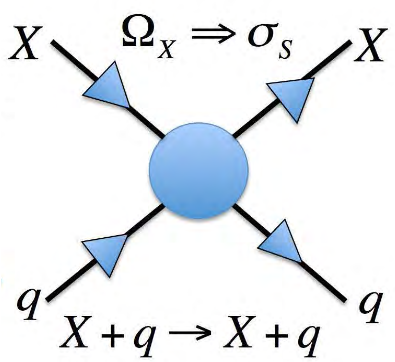
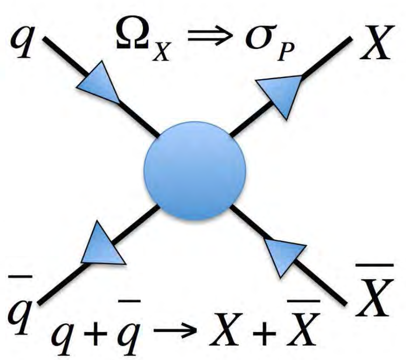


Creation at the LHC



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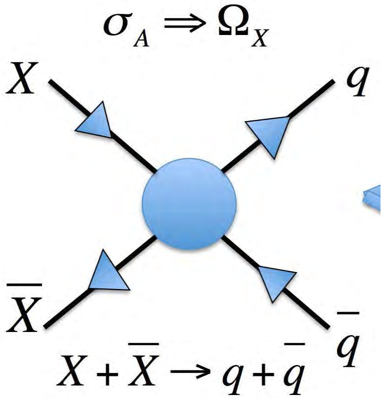

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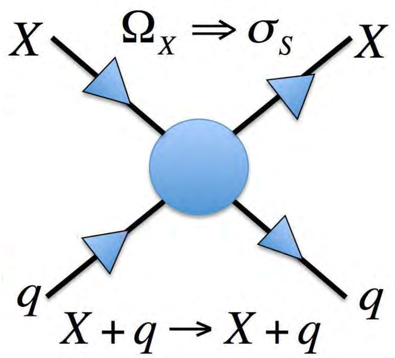

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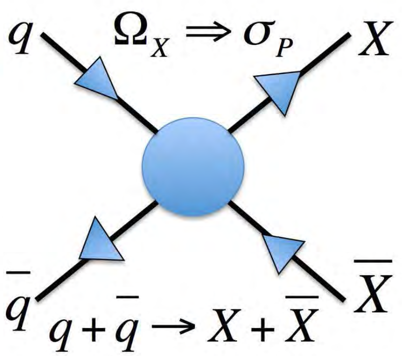

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But we have to look elsewhere !

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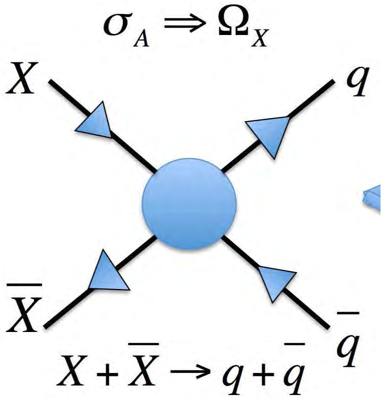

$\sigma_A \Rightarrow \Omega_X$

$X + \bar{X} \to q + \bar{q}$

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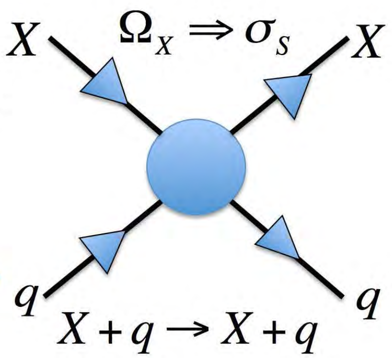
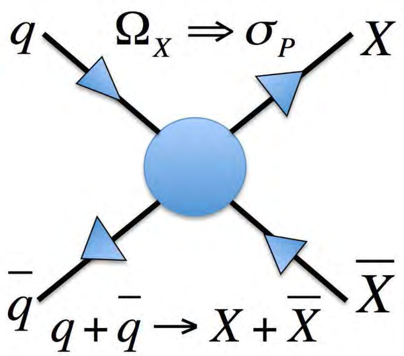


$\Omega_X \Rightarrow \sigma_S$

$X + q \to X + q$

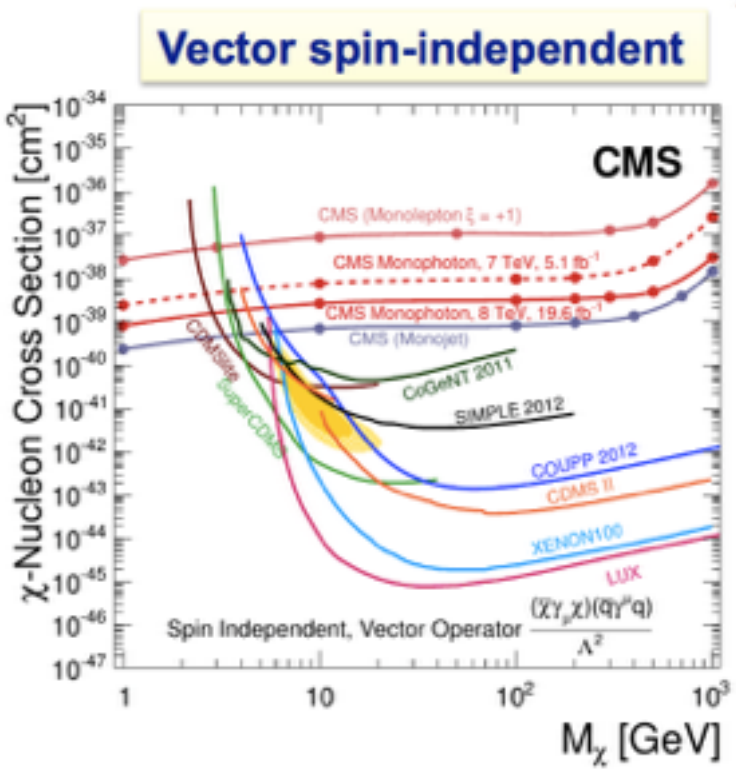
Creation at the LHC



$\Omega_X \Rightarrow \sigma_P$

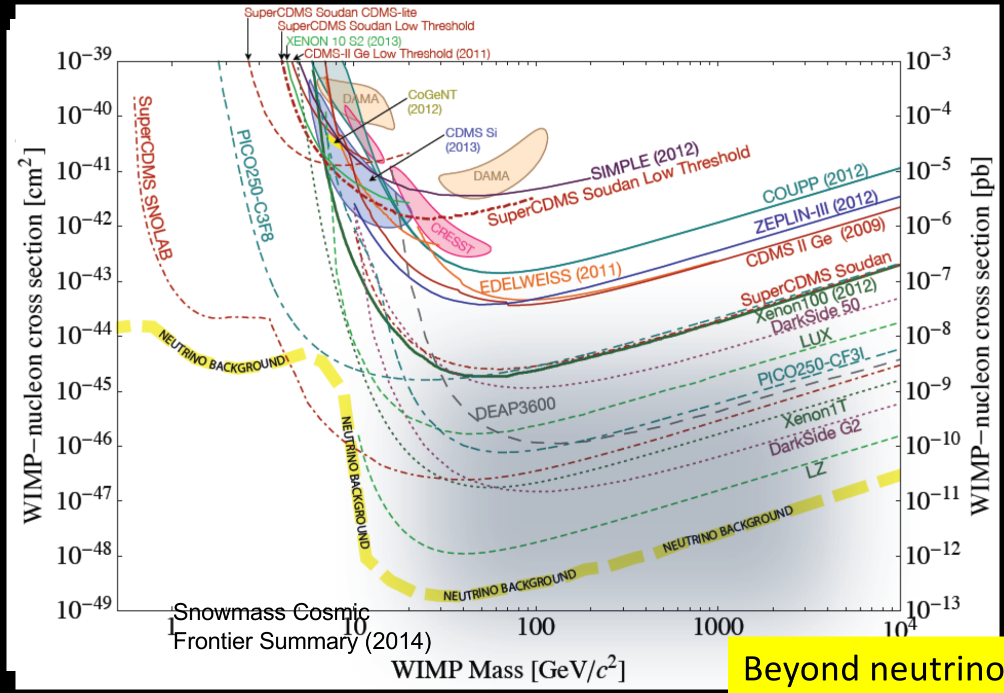
$q + \bar{q} \to X + \bar{X}$

DM Searches



DIRECT DETECTION: STATUS AND PROSPECTS

- Since 2010, sensitivity improved by ~100 (for m ~ 100 GeV)
- Further improvements by 2-3 orders of magnitude expected by a suite of experiments world-wide

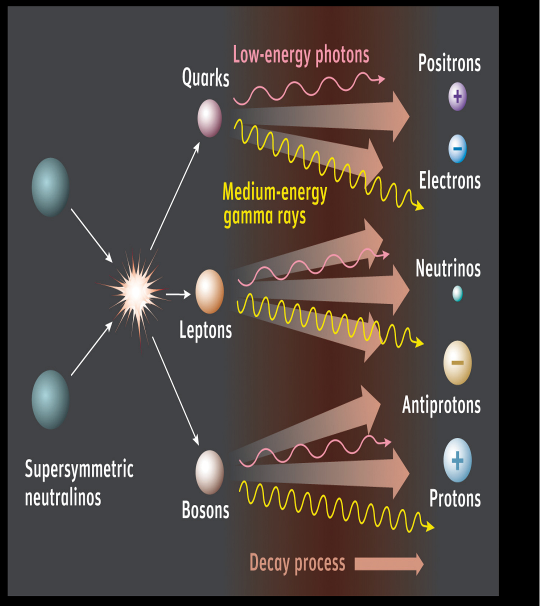


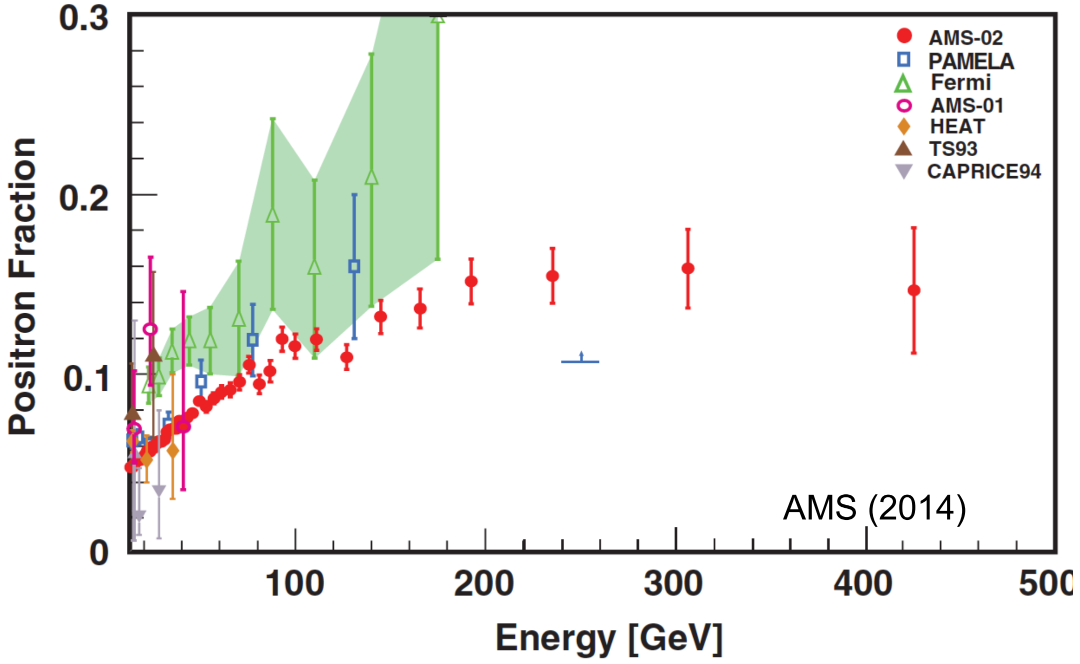
ICHEP 2016 -- I. Shipsey

Beyond neutrino floor
directional detection needed

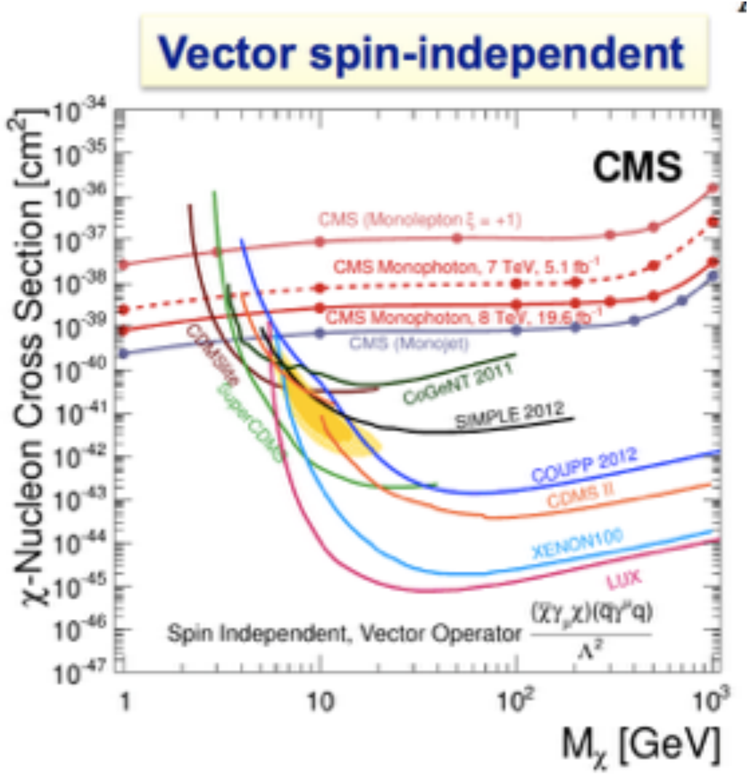
INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to
  - Positrons
  - High-Energy Photons
  - Neutrinos
  - Antiprotons
  - Antideuterons
  - …





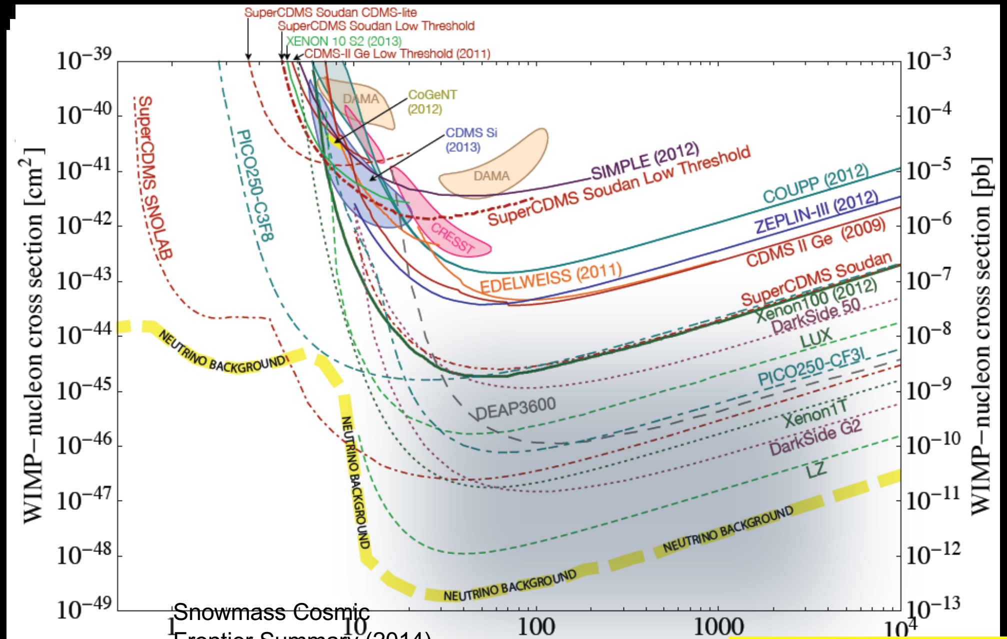
DM Searches



- *Already close to neutrino floor*

DIRECT DETECTION: STATUS AND PROSPECTS

- Since 2010, sensitivity improved by ~100 (for m ~ 100 GeV)
- Further improvements by 2-3 orders of magnitude expected by a suite of experiments world-wide

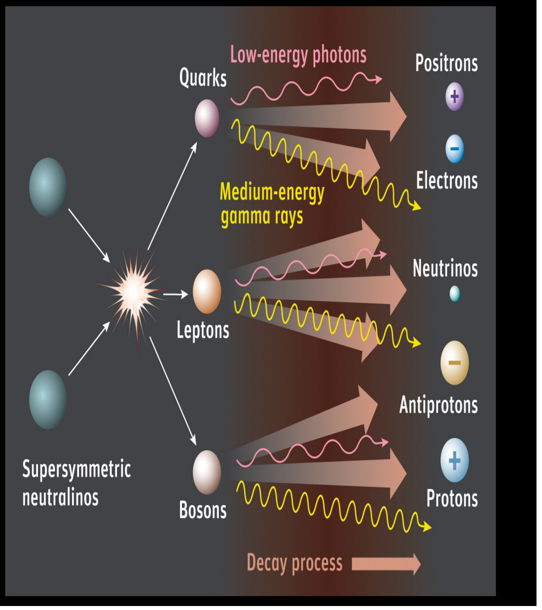


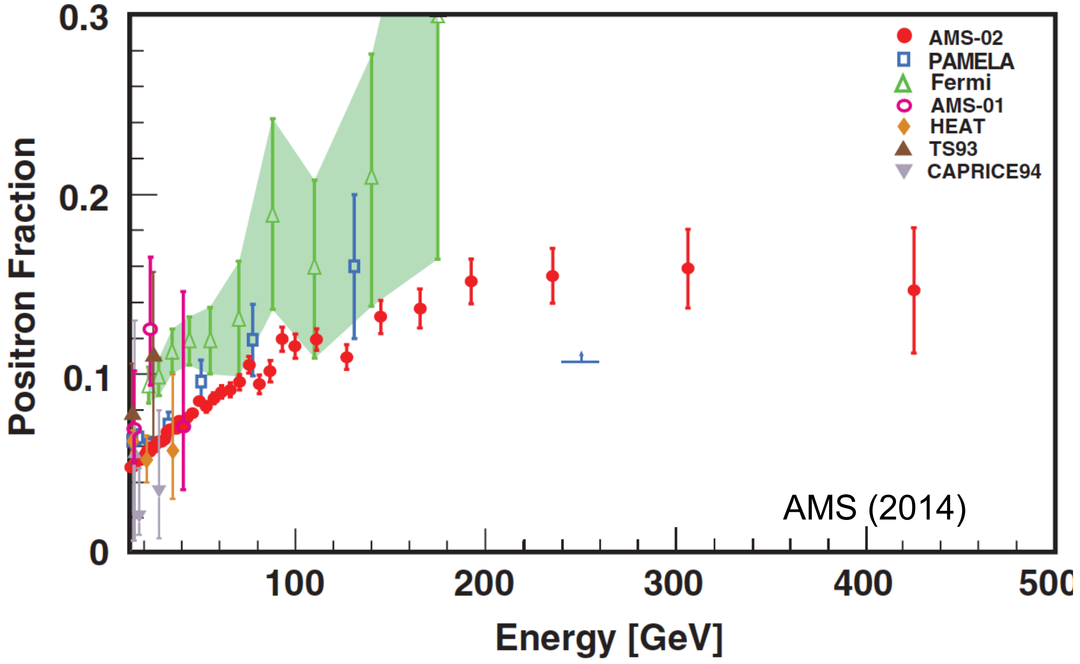
ICHEP 2016 -- I. Shipsey

Beyond neutrino floor
directional detection needed

INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to
  - Positrons
  - High-Energy Photons
  - Neutrinos
  - Antiprotons
  - Antideuterons
  - …





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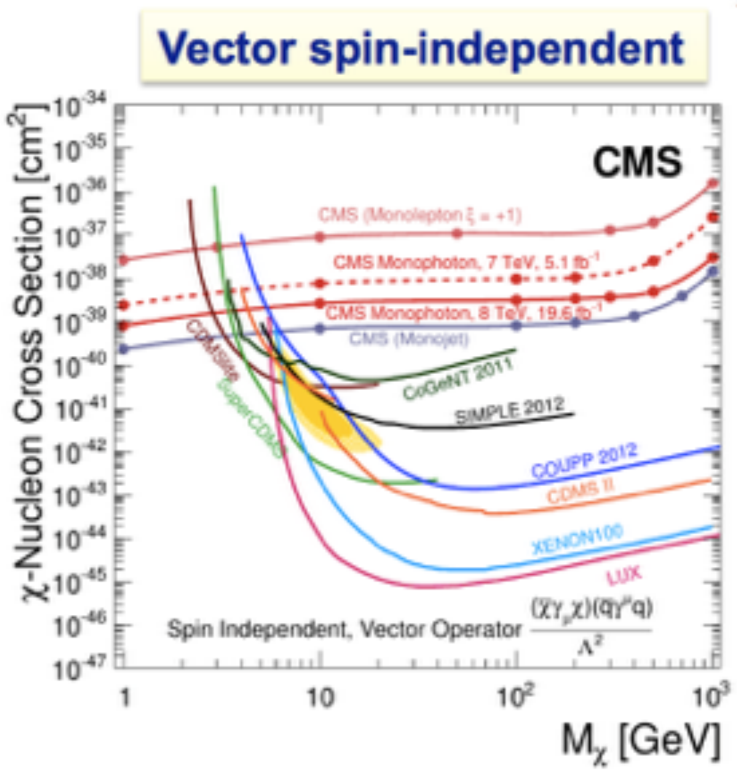

- *Already close to neutrino floor*
- *Still have a chance*

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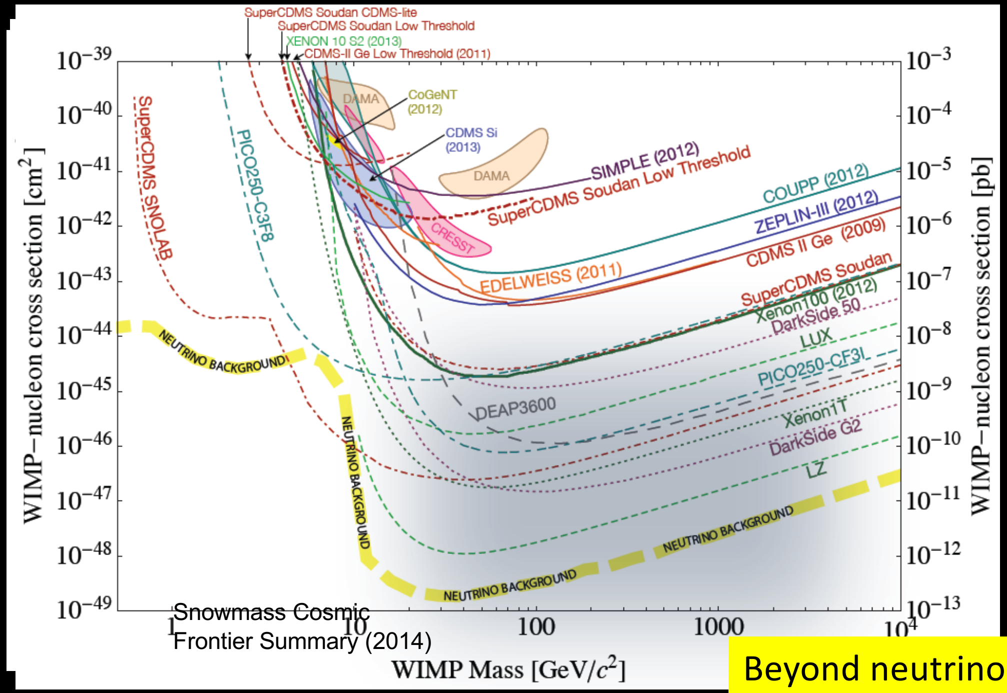

ICHEP 2016 -- I. Shipsey

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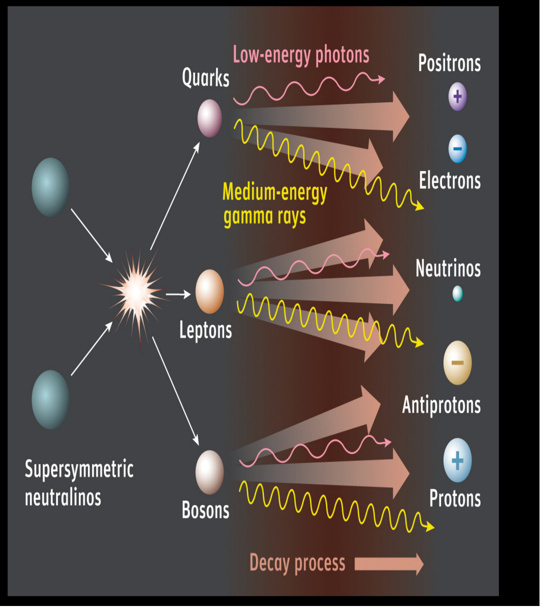
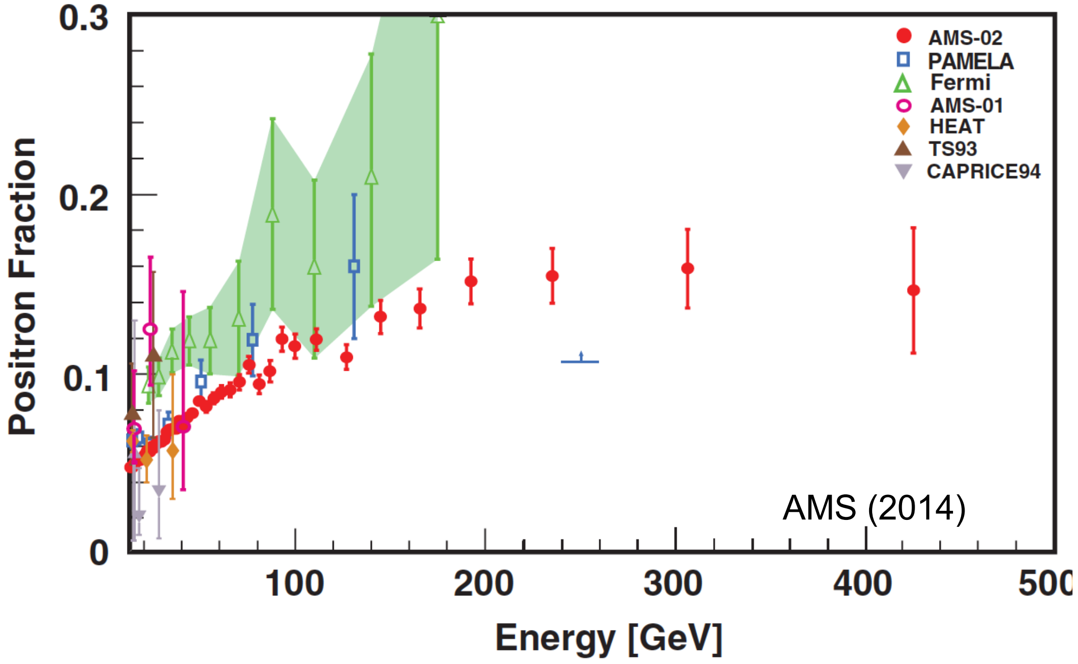
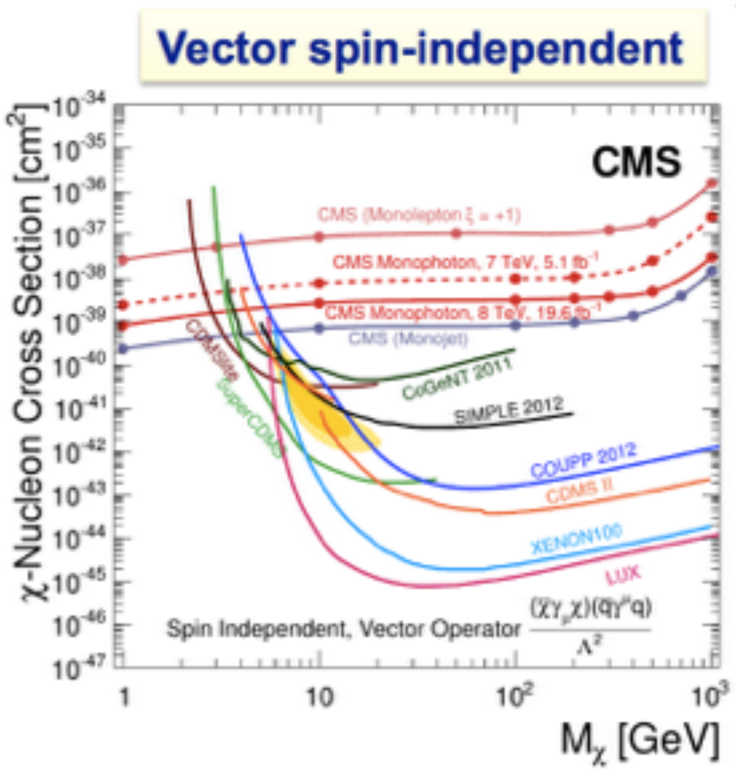




DM Searches



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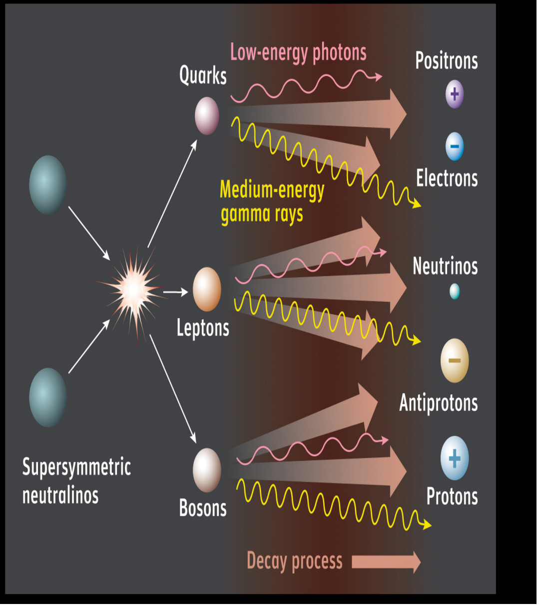

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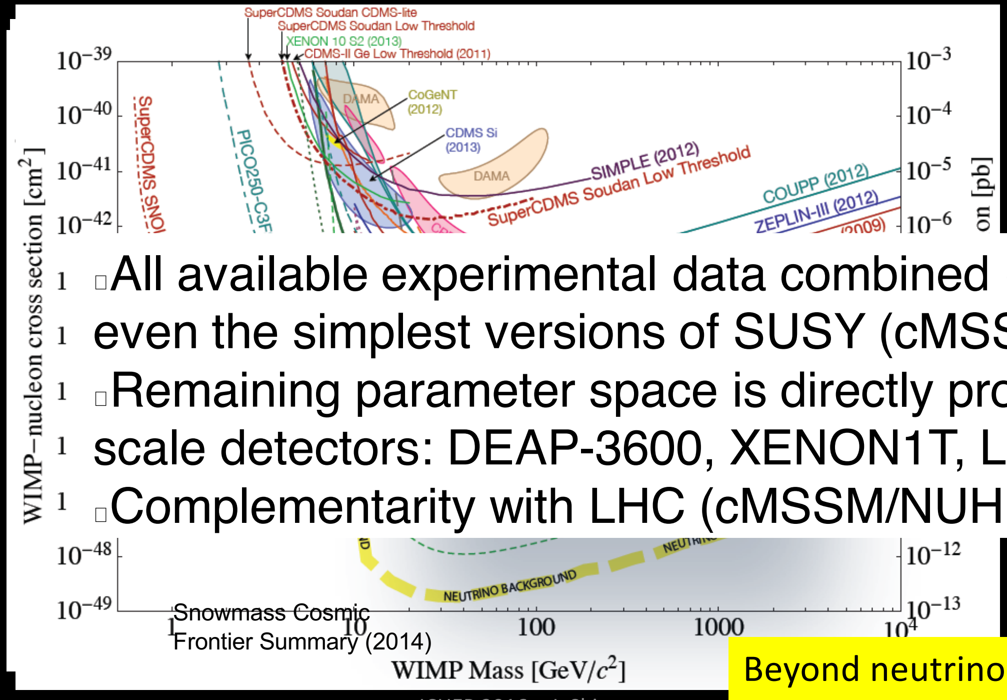
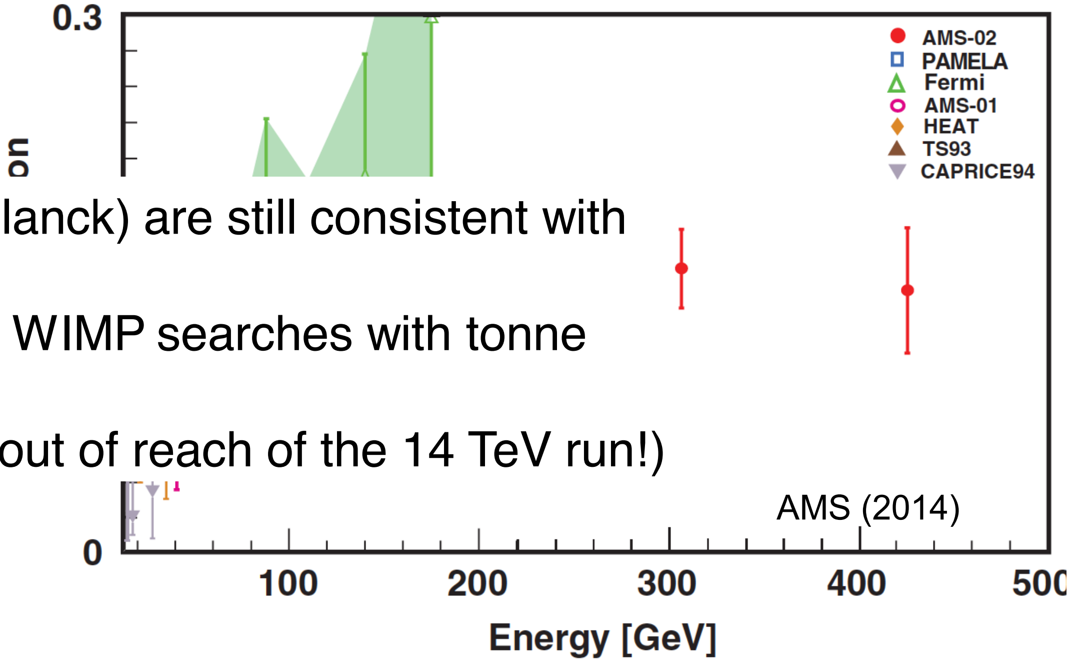




- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

Beyond neutrino floor directional detection needed

ICHEP 2016 -- I. Shipsey

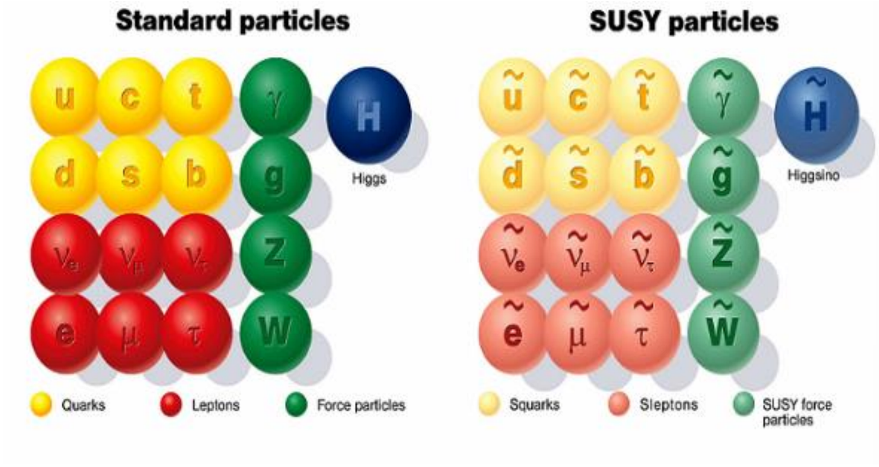
Search for New Physics

SUSY

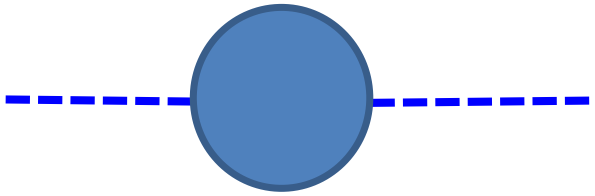
Supersymmetry - Target # 3

SUSY has been the prime candidate for BSM physics near the TeV scale.

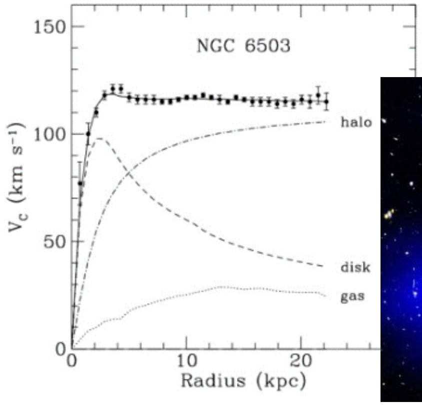
Kiwoon Choi
(ICHEP 2016, Chicago)

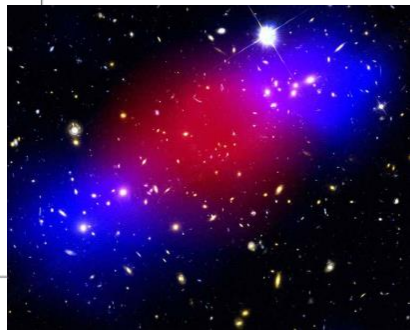


Hierarchy problem

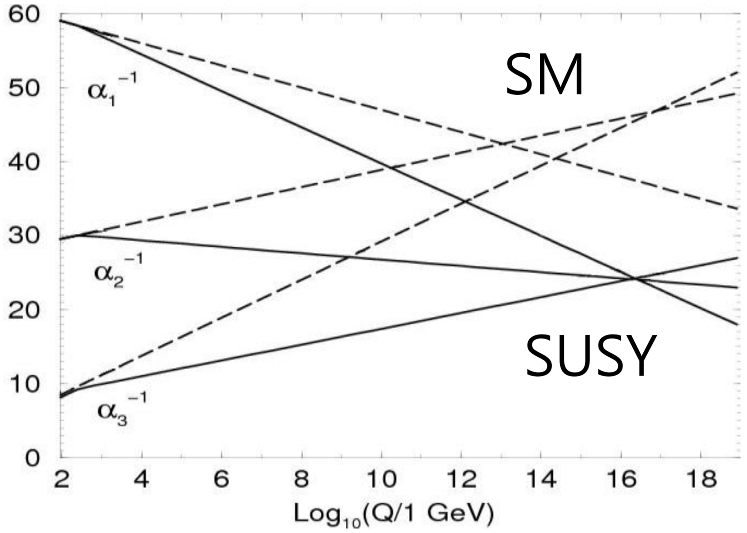


$$\delta m_H^2 \sim M_{\text{Planck}}^2 \Rightarrow m_{\text{SUSY}}^2$$

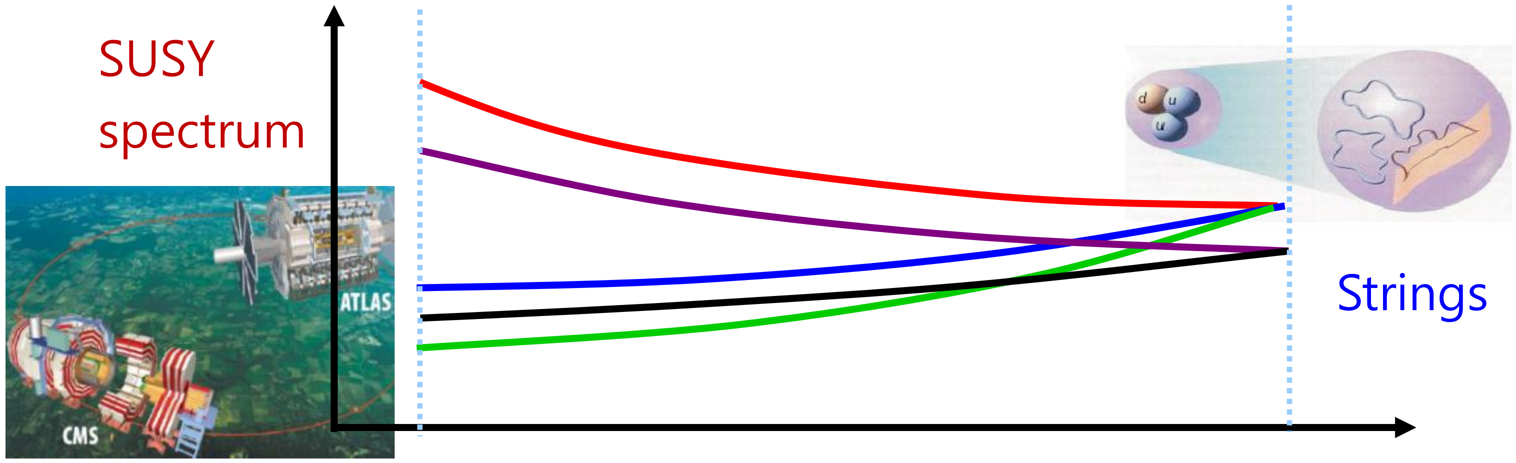




Dark matter



Gauge coupling unification



1 TeV

10^{16} GeV

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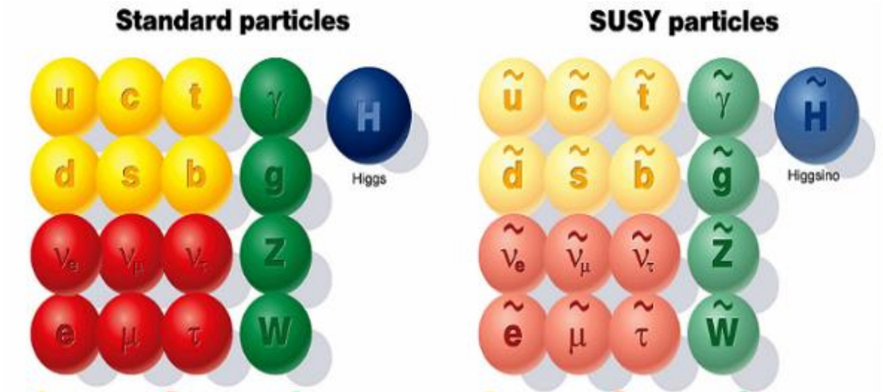

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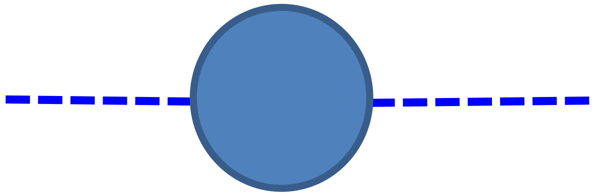
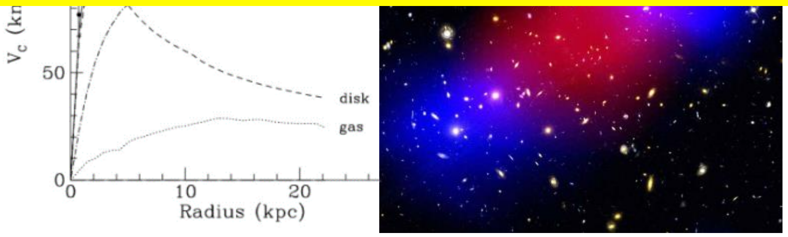
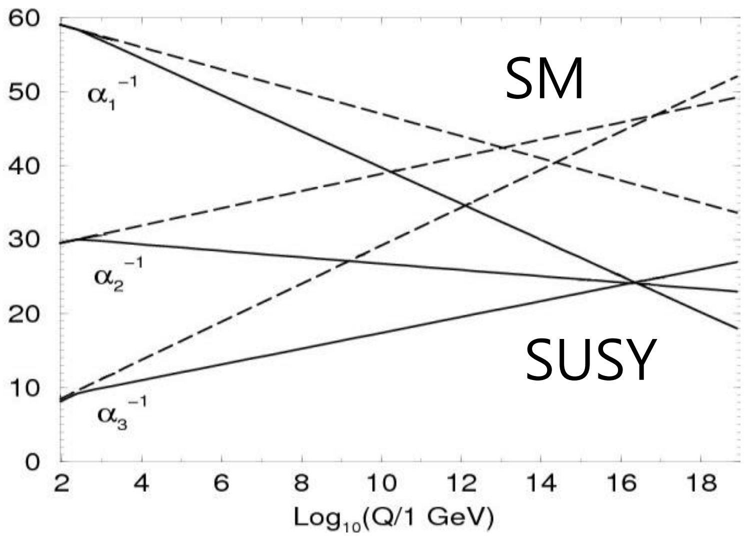


$$\delta m_H^2 \sim M_{\rm Planck}^2 \;\Rightarrow\; m_{\rm SUSY}^2$$

Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics





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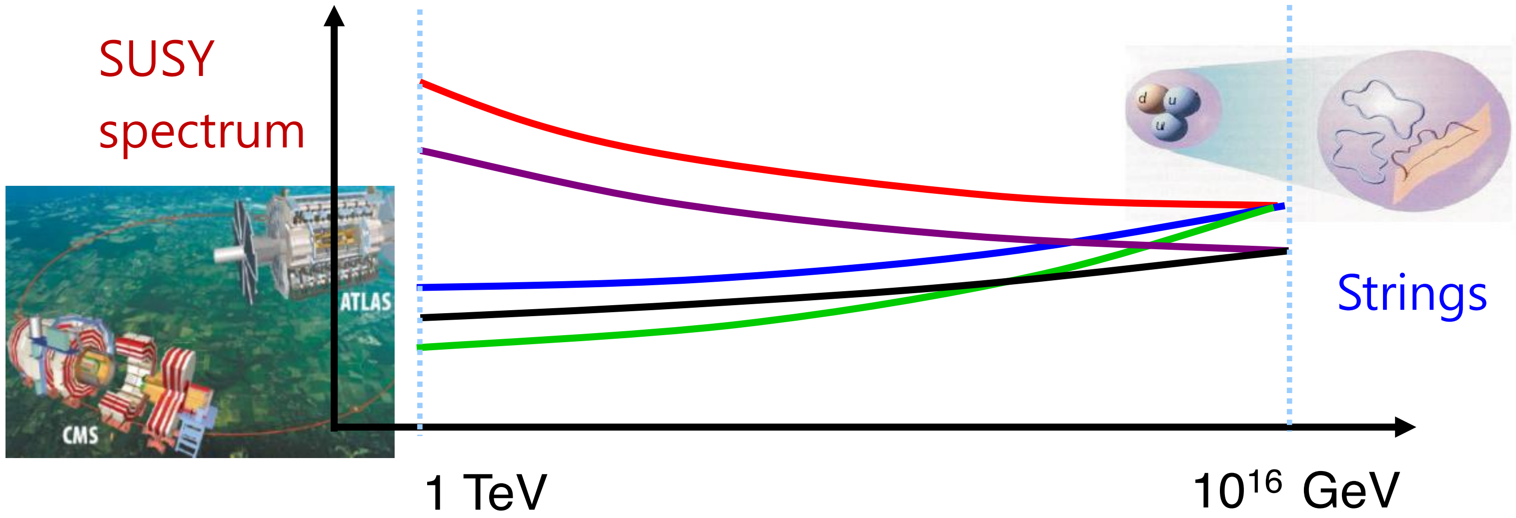

What is the LHC Reach?

What is the LHC Reach?

Universal scenario

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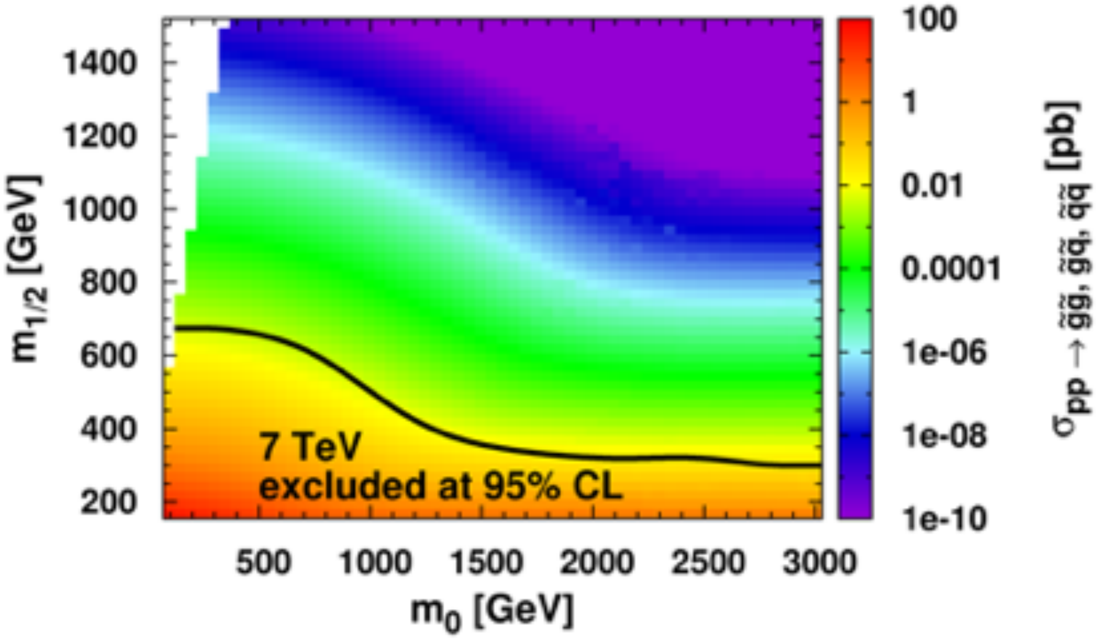
Universal scenario



What is the LHC Reach?

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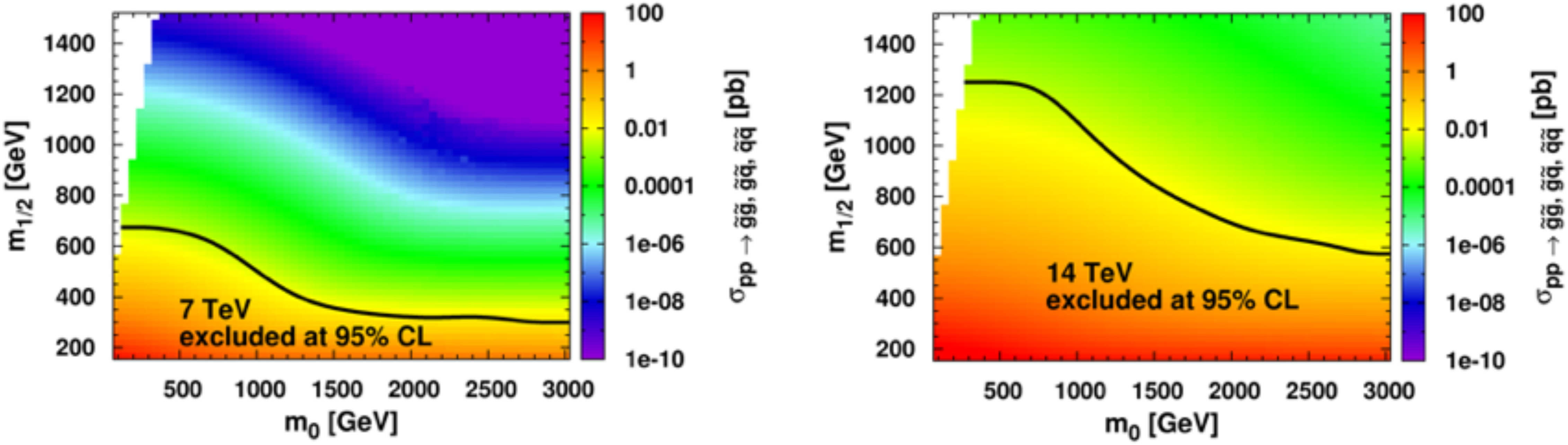

What is the LHC Reach?

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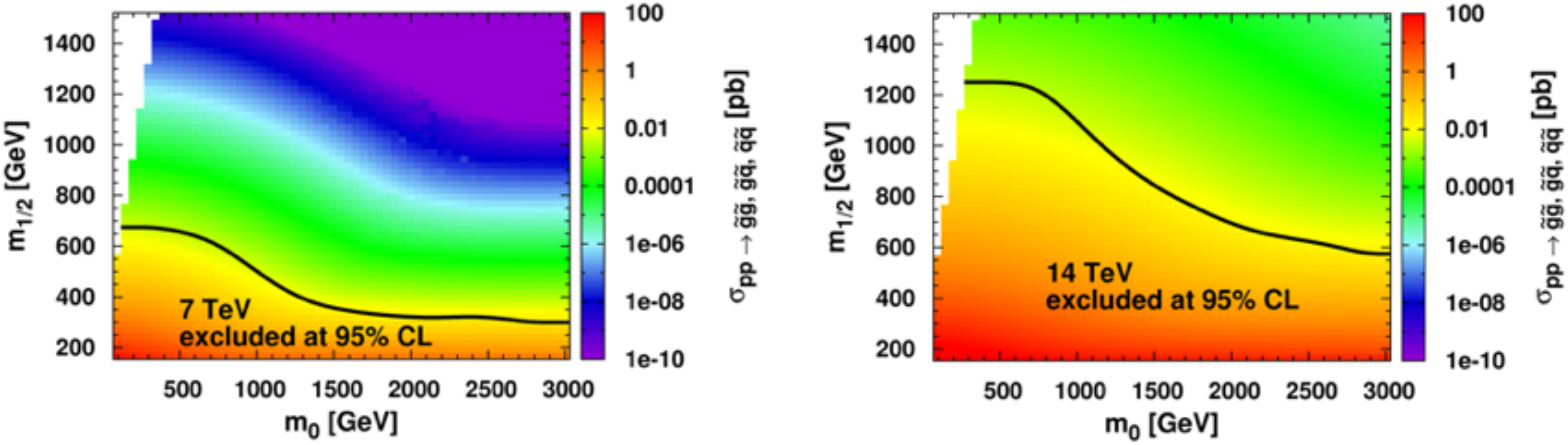

Masses of superpartners

What is the LHC Reach?

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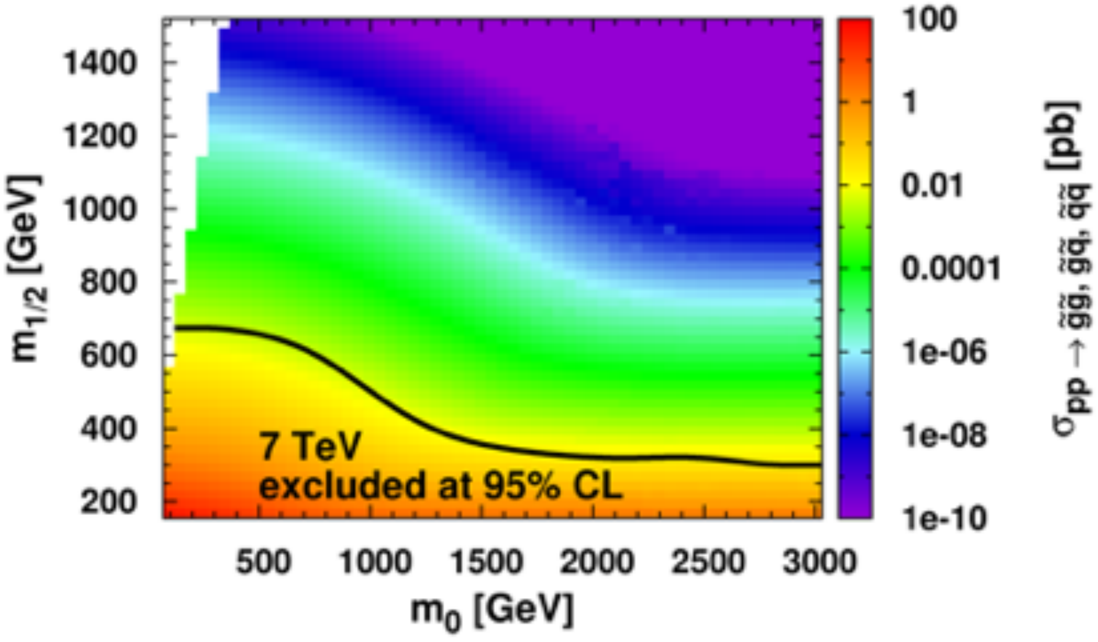
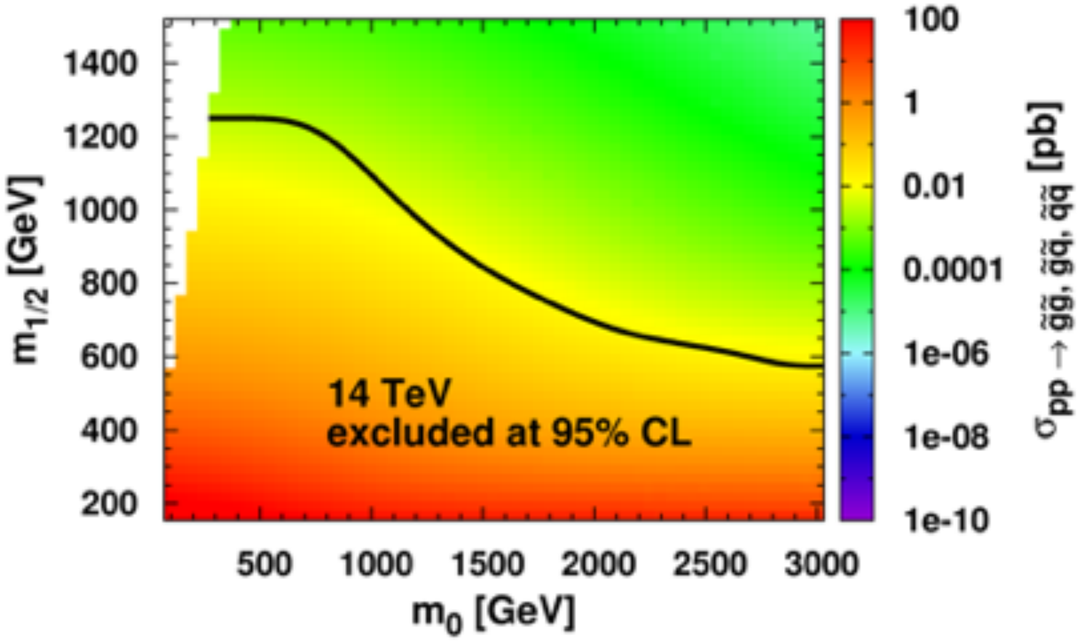
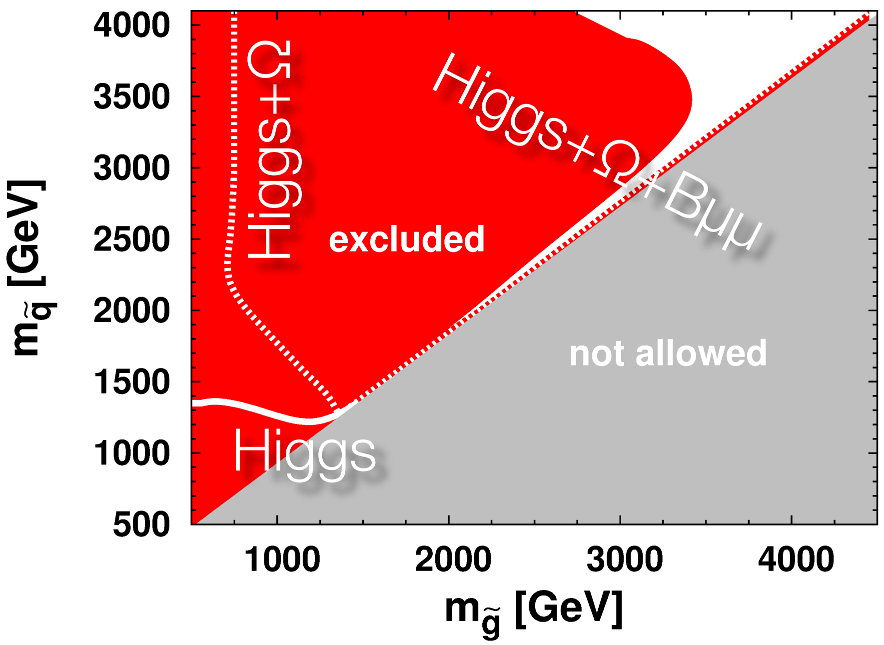


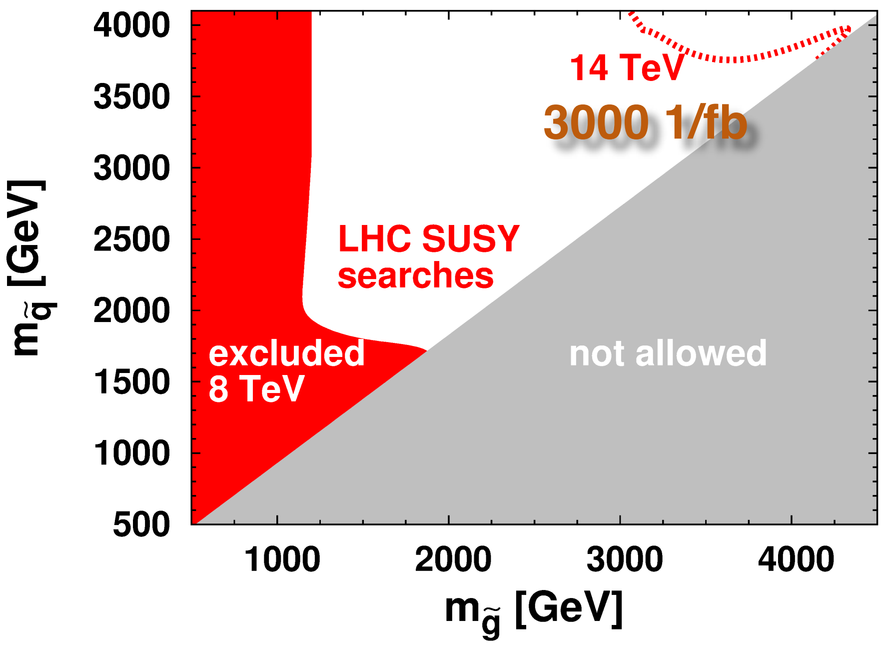


Masses of superpartners

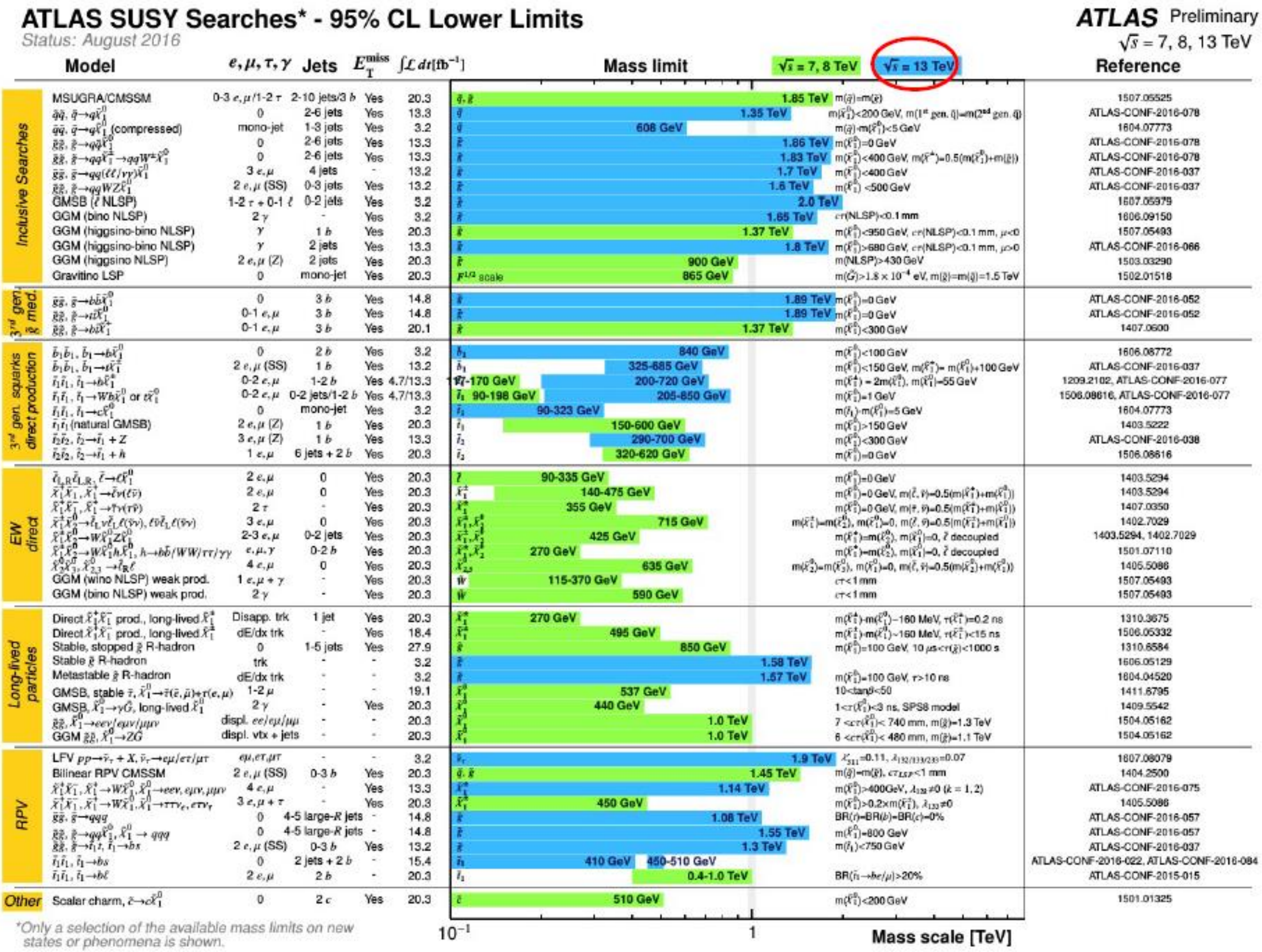
CMSSM



NMSSM



LHC Run2



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{q}$ 1.35 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.86 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.83 TeV	$m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, $\mu<0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, $\mu>0$	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$ 325-685 GeV	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^\pm)$= $m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e,μ	1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^\pm)$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 90-198 GeV 🟦 205-850 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	🟦 $\tilde{t}_2$ 290-700 GeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 140-475 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 355 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu),\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 715 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 425 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^\pm$ 495 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.45 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}_1^\pm$ 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	🟦 $\tilde{g}$ 1.3 TeV	$m(\tilde{t}_1)$<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

LHC Run2

Question to experimentalists:
SUSY is so nice, why don't you see it?

Search for New Physics

Extra Dimensions/ Exotics

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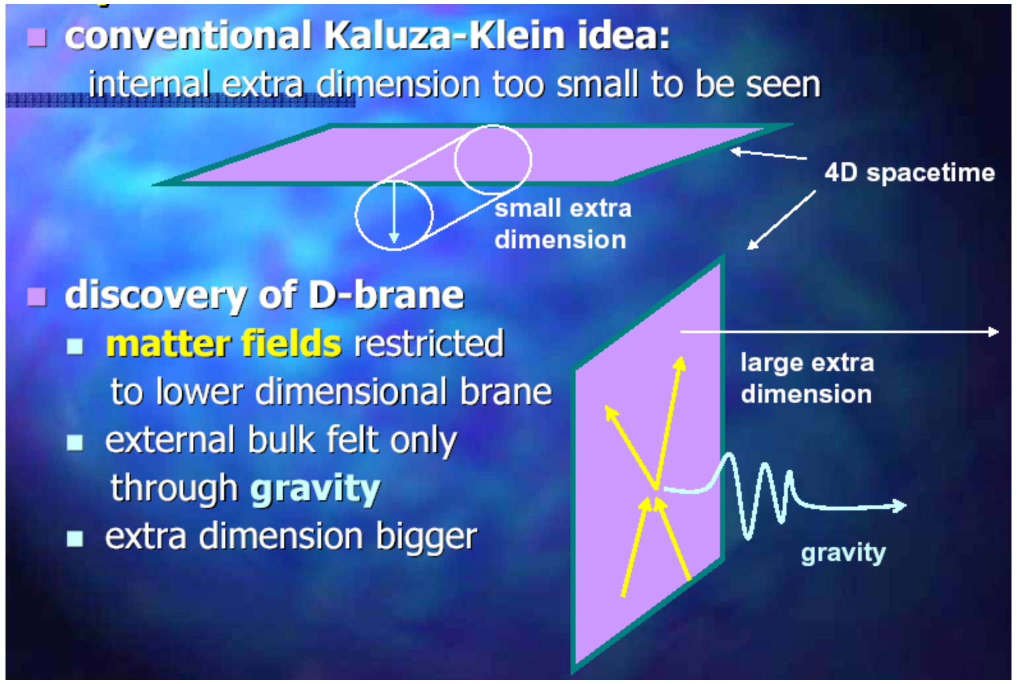
Extra Dimensions/ Exotics



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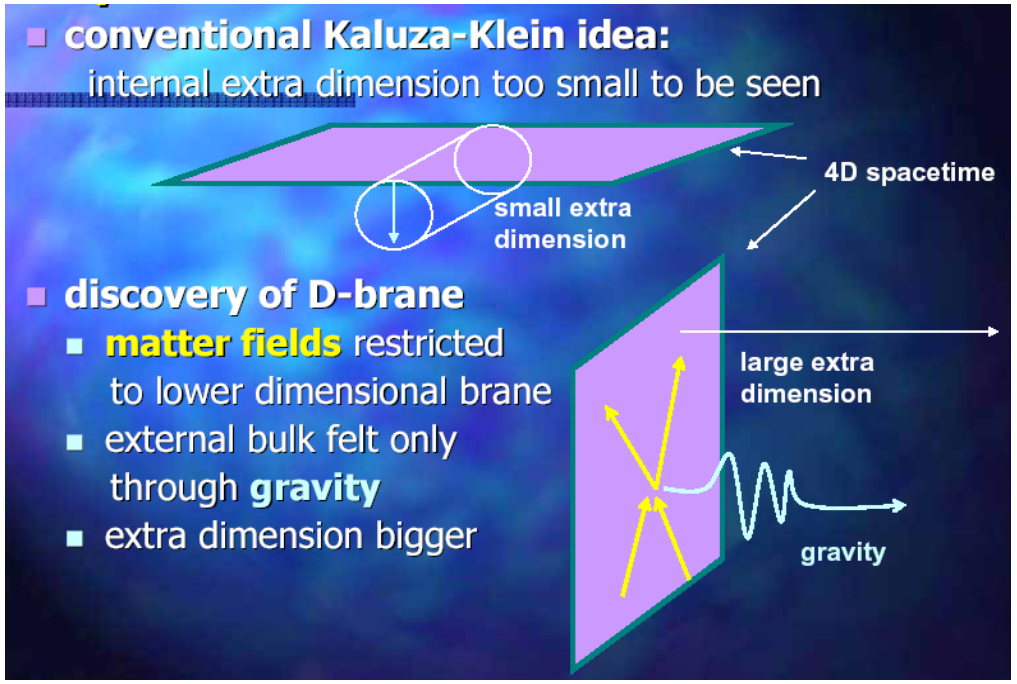

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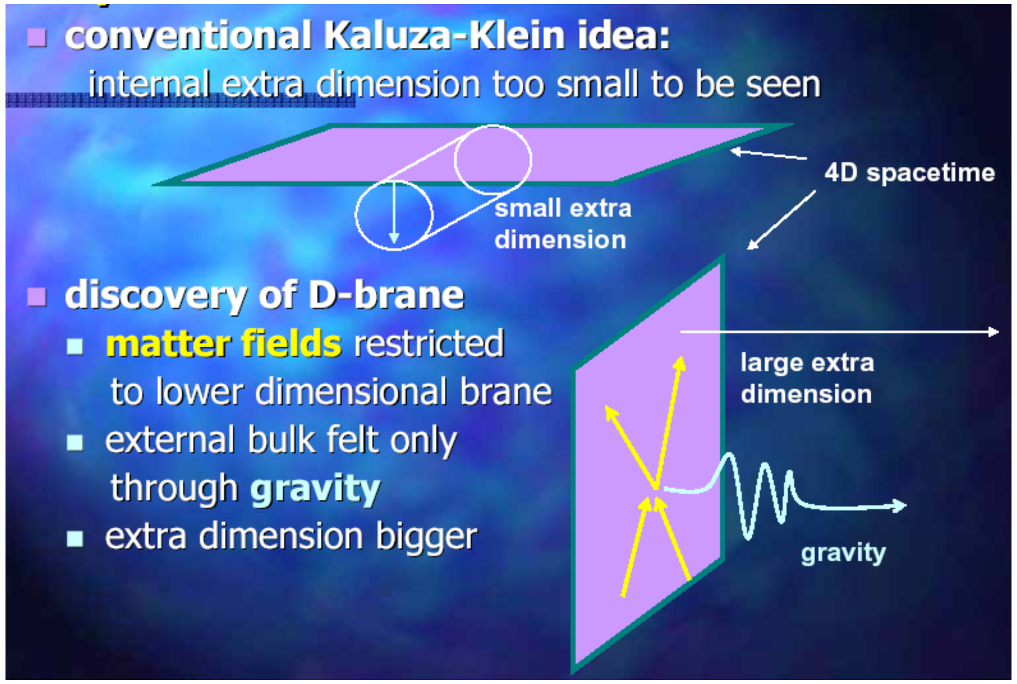

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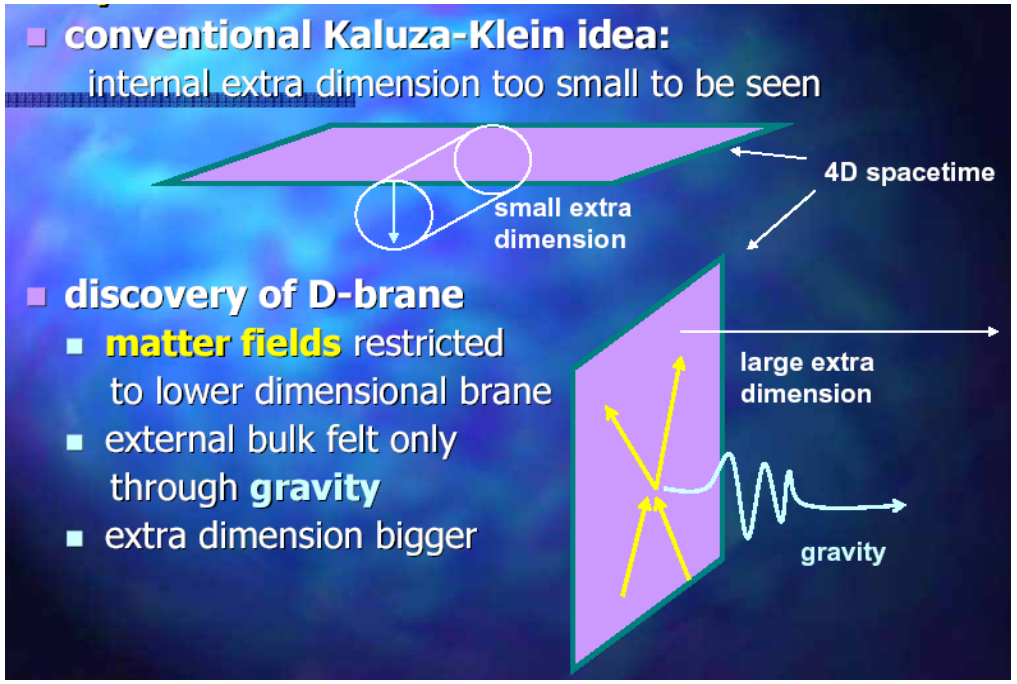

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Q: Do we have good reasons to believe in it?

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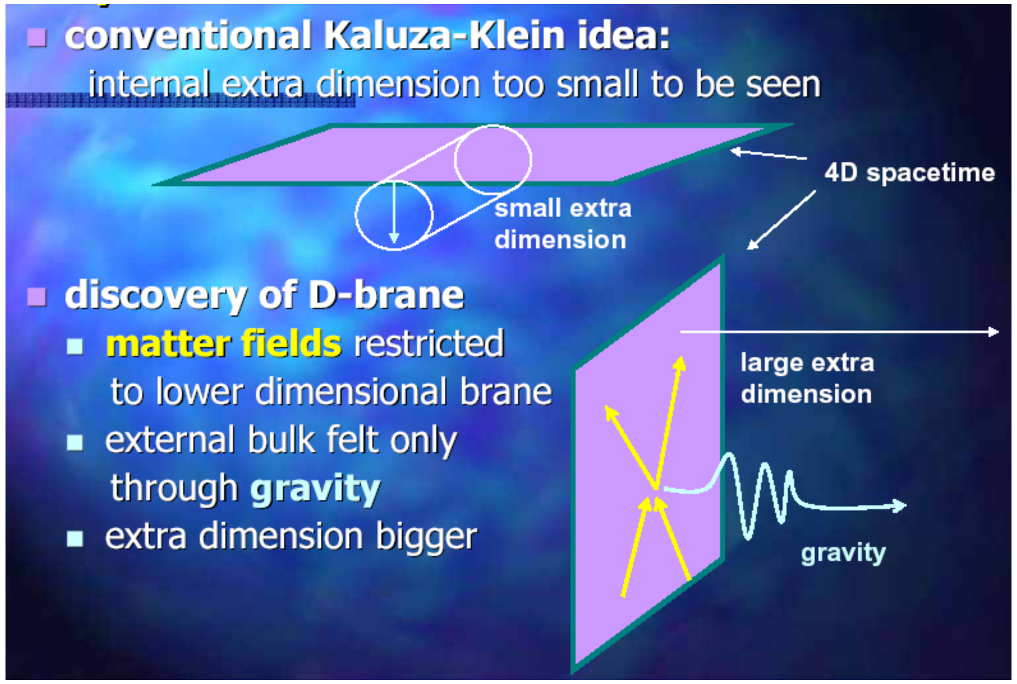

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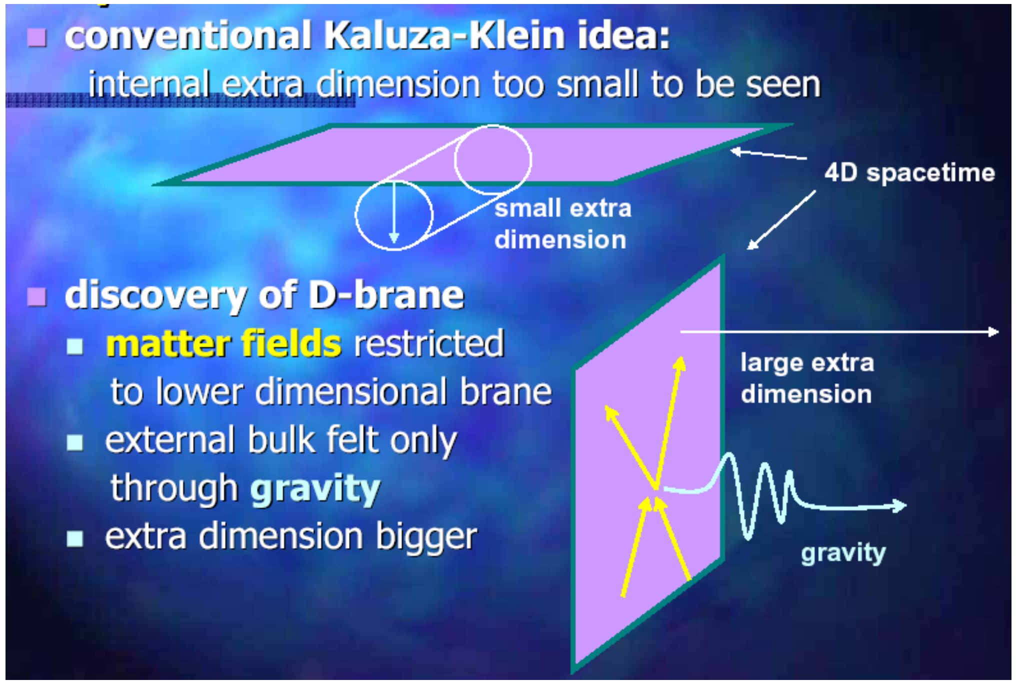

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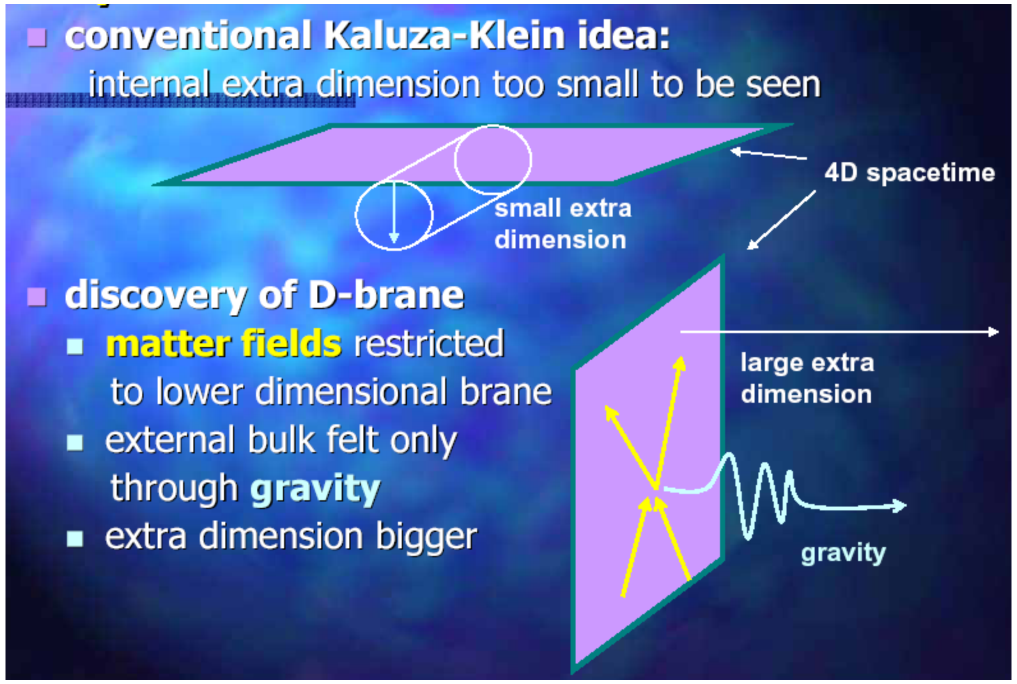

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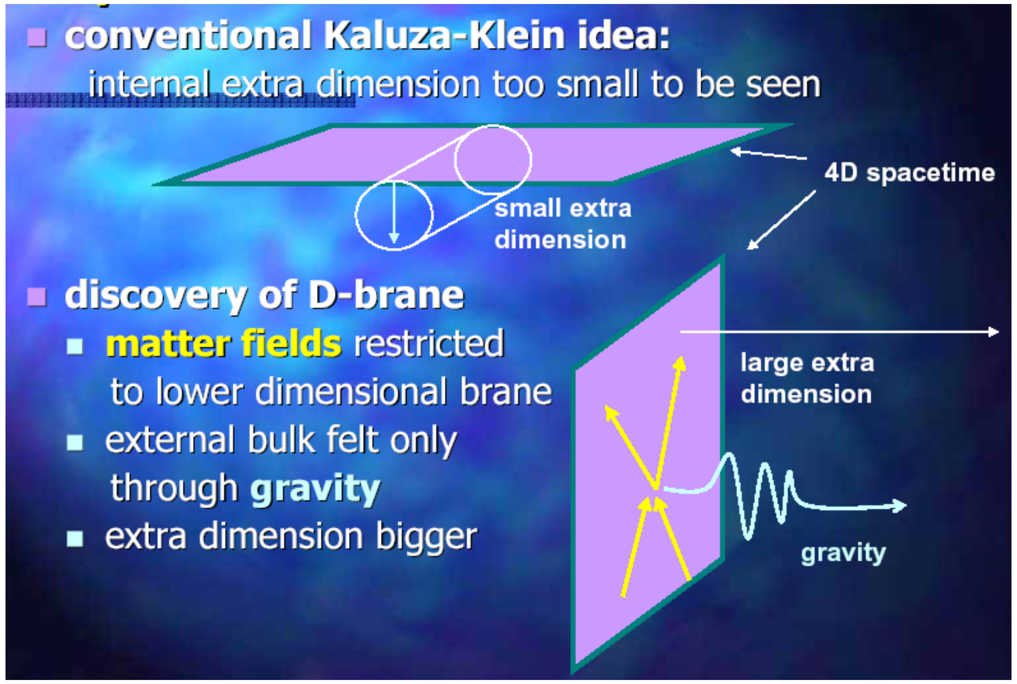

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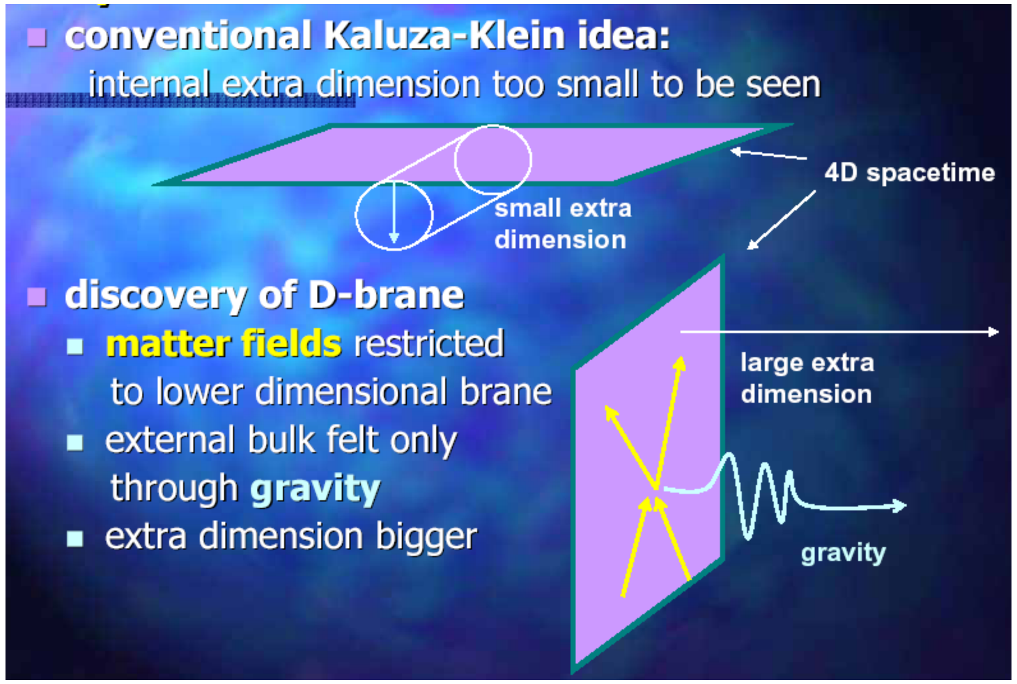

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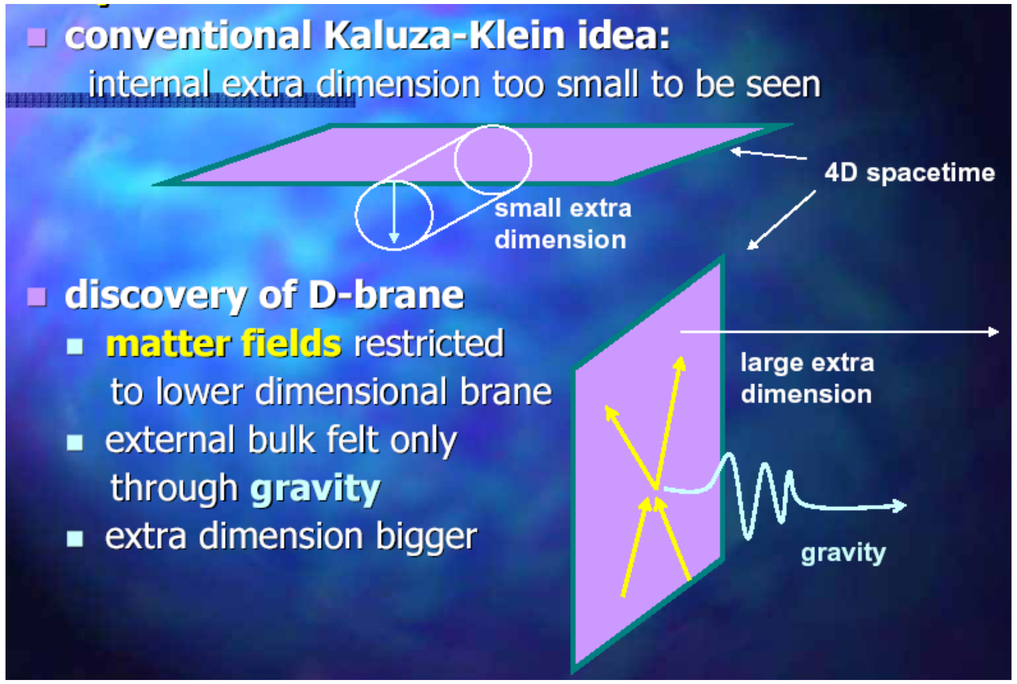

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Experiment

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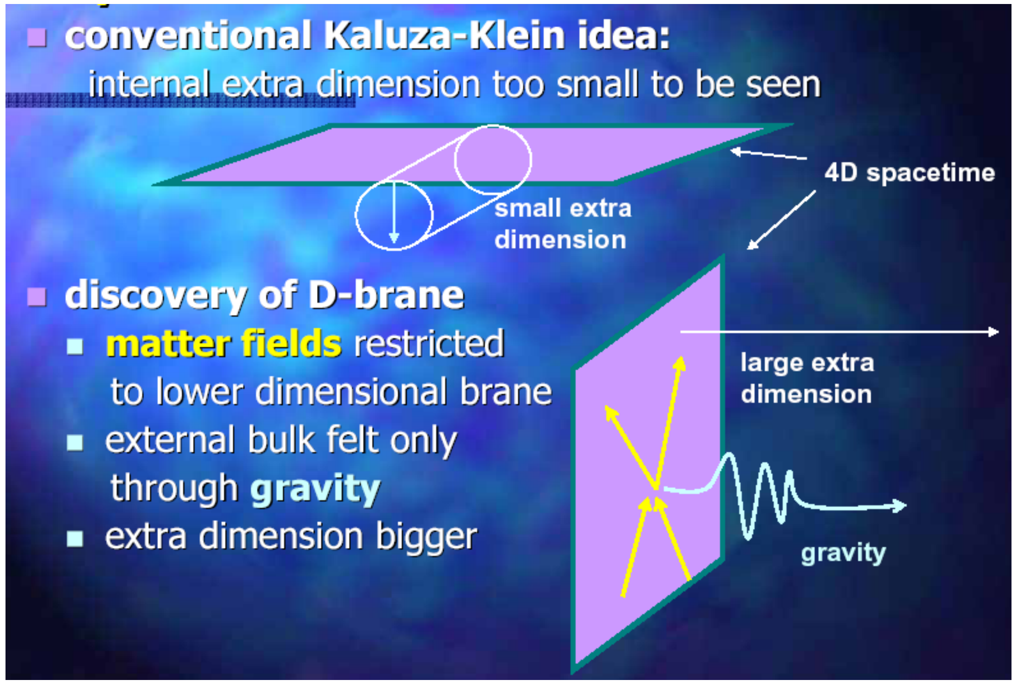

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- Search for Z' (Di-muon events)

Search for New Physics

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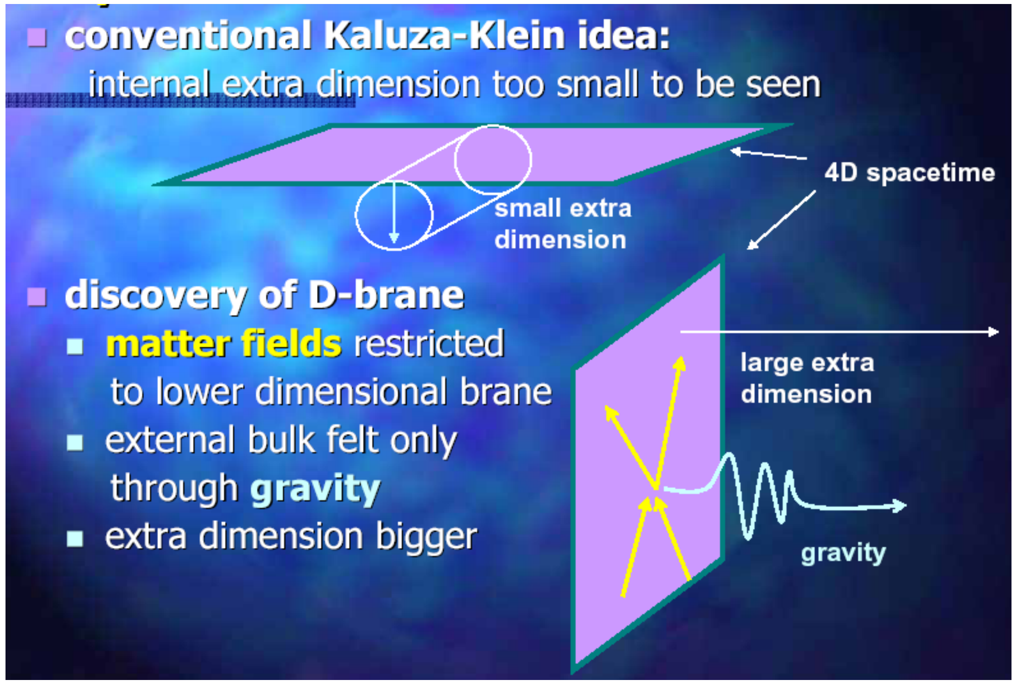

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Experiment

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- Search for W’ (single muon/ jets)

Search for New Physics

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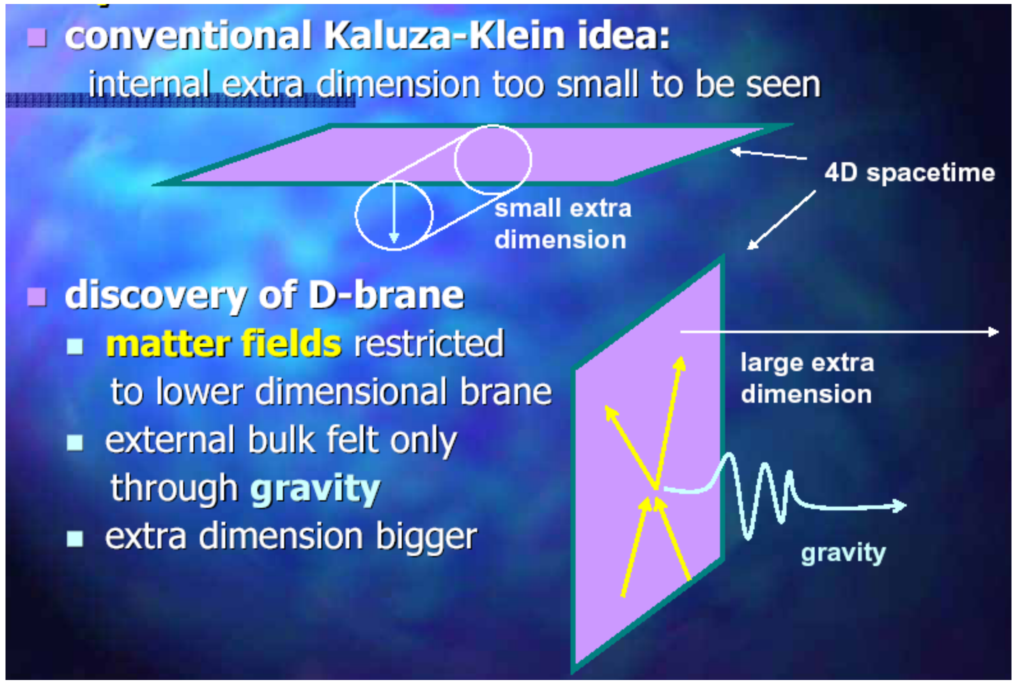

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Experiment

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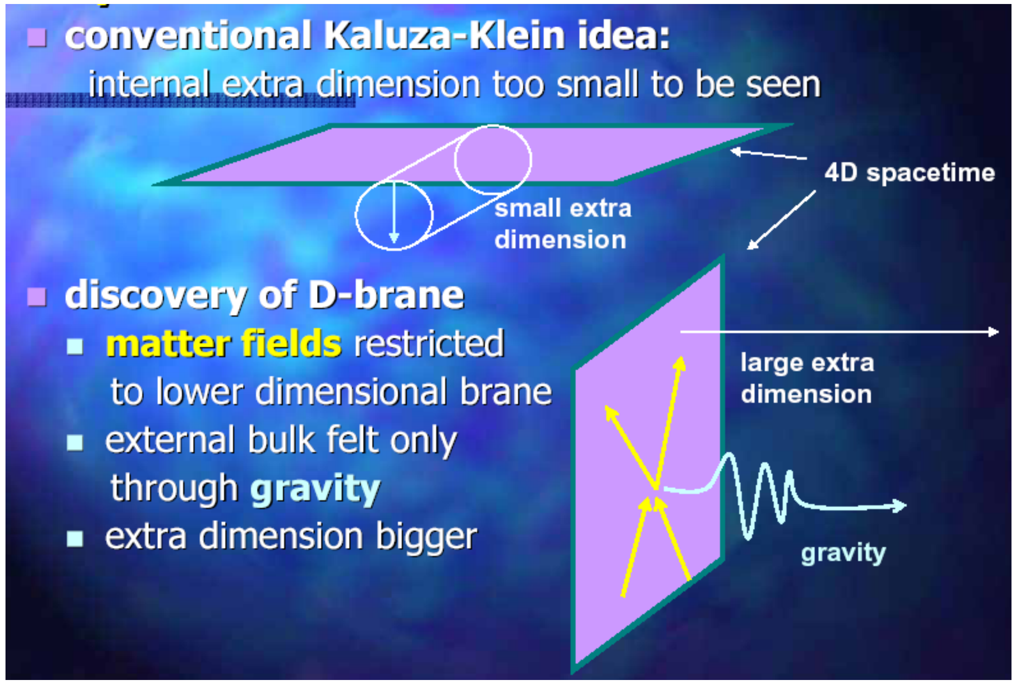

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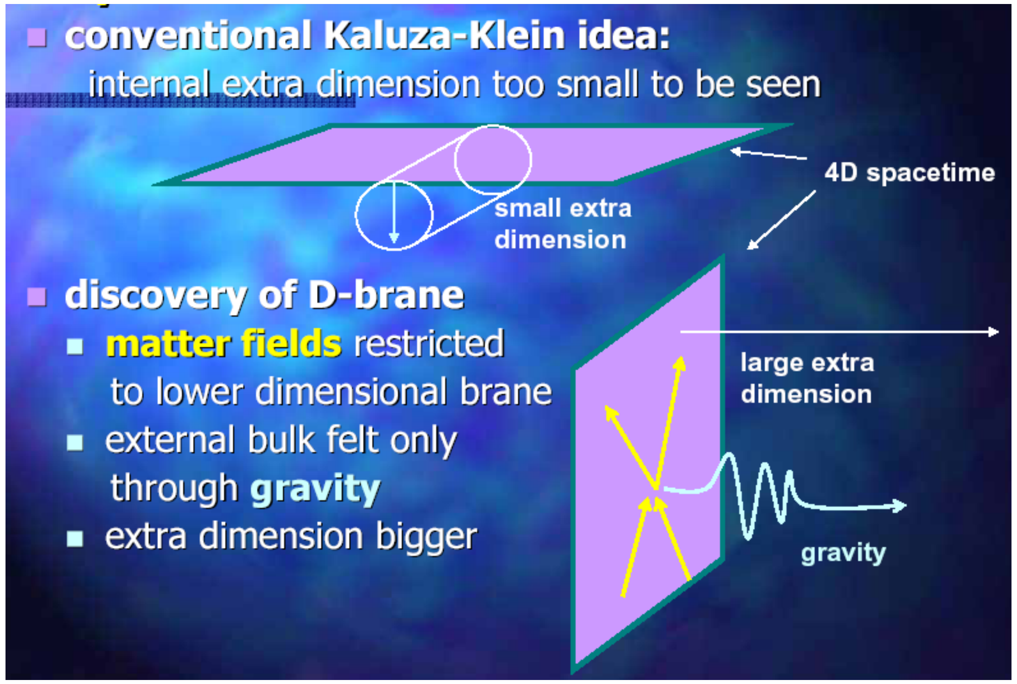

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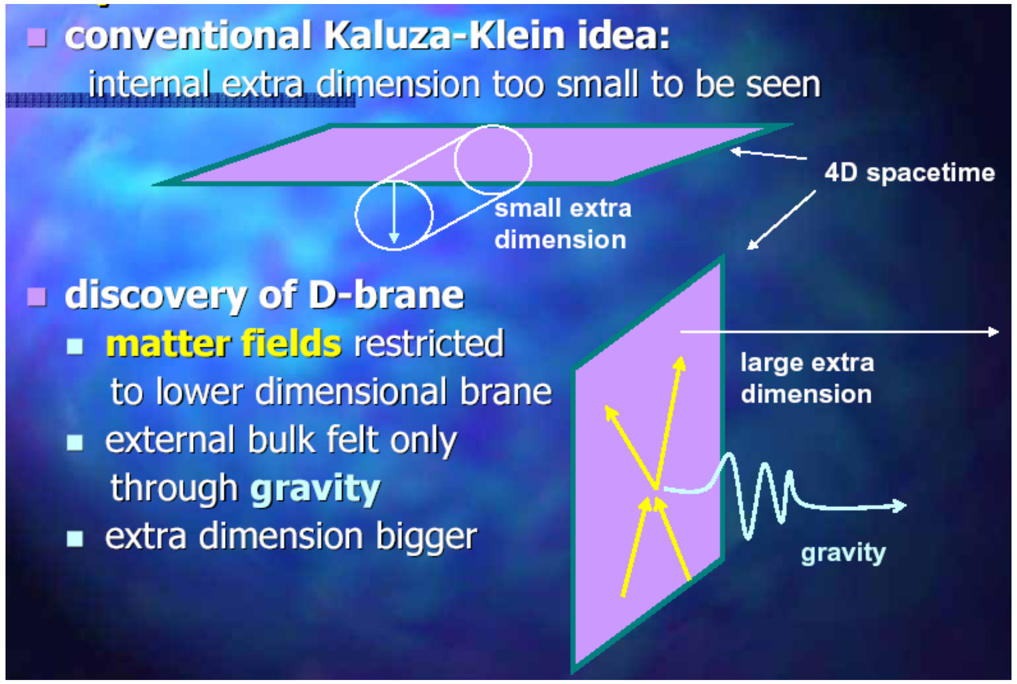
Search for New Physics

Extra Dimensions/ Exotics



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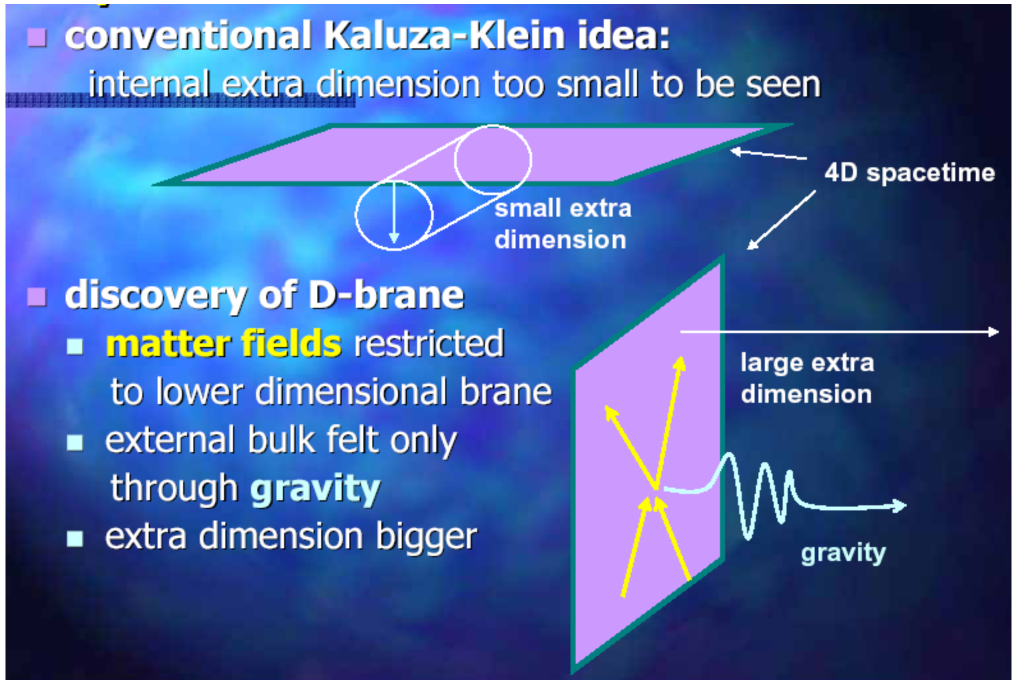

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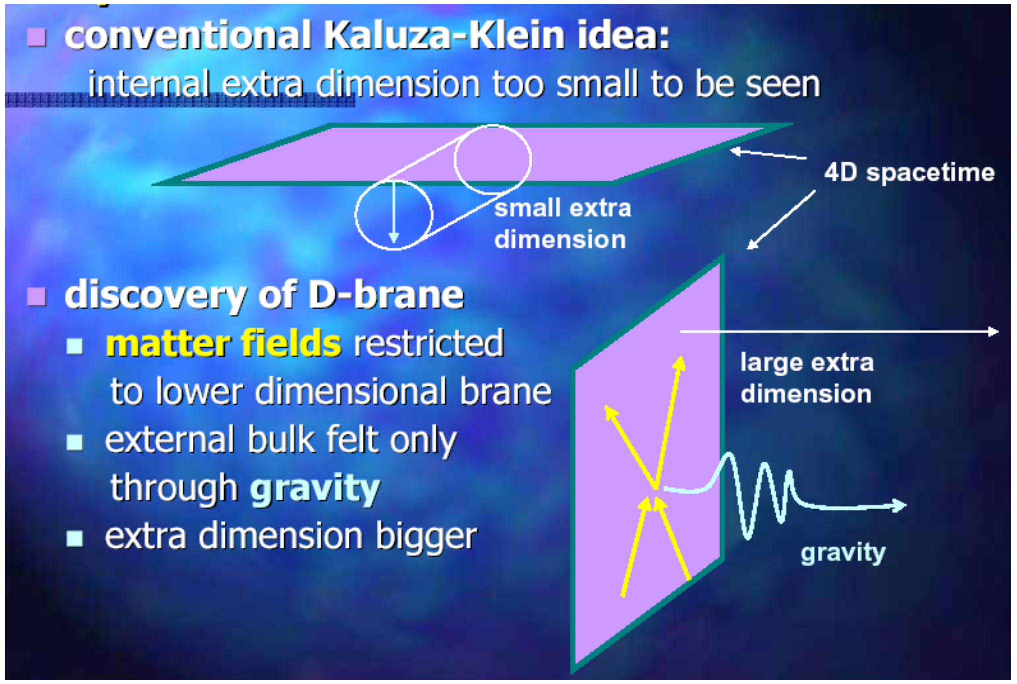
Exotics

- Leptoquarks

Search for New Physics

Extra Dimensions/ Exotics



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Search for New Physics

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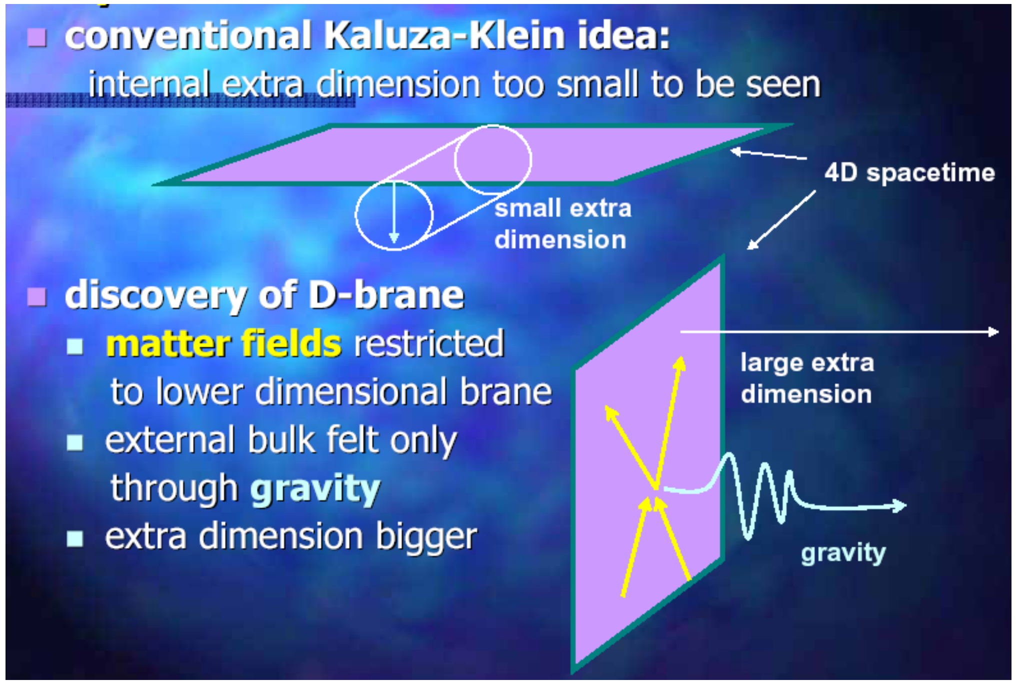

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- Off-pointing photons

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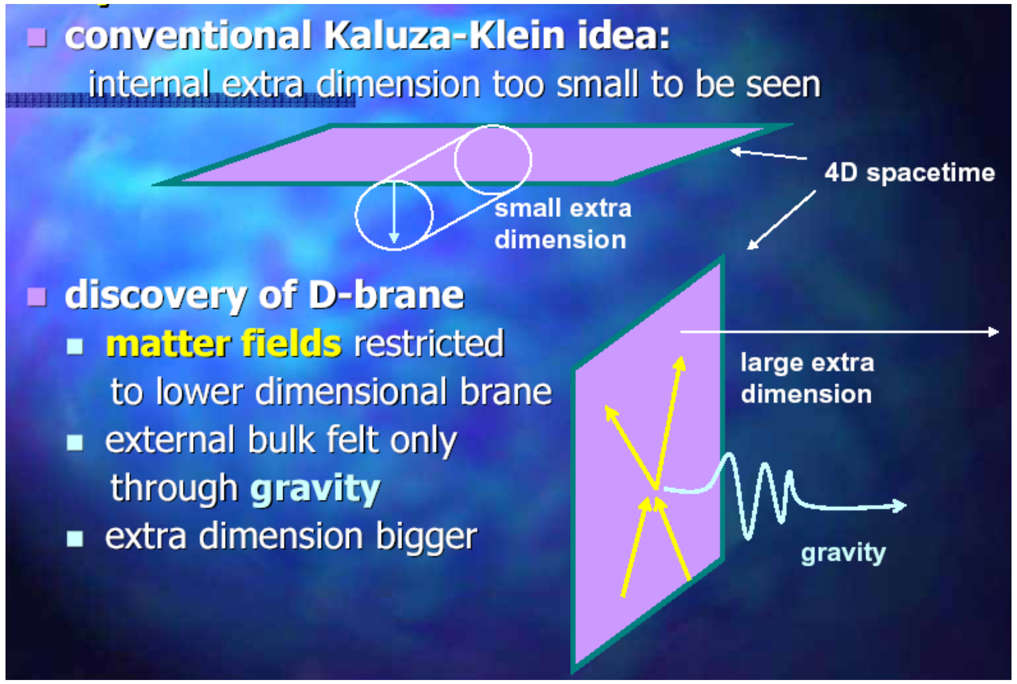

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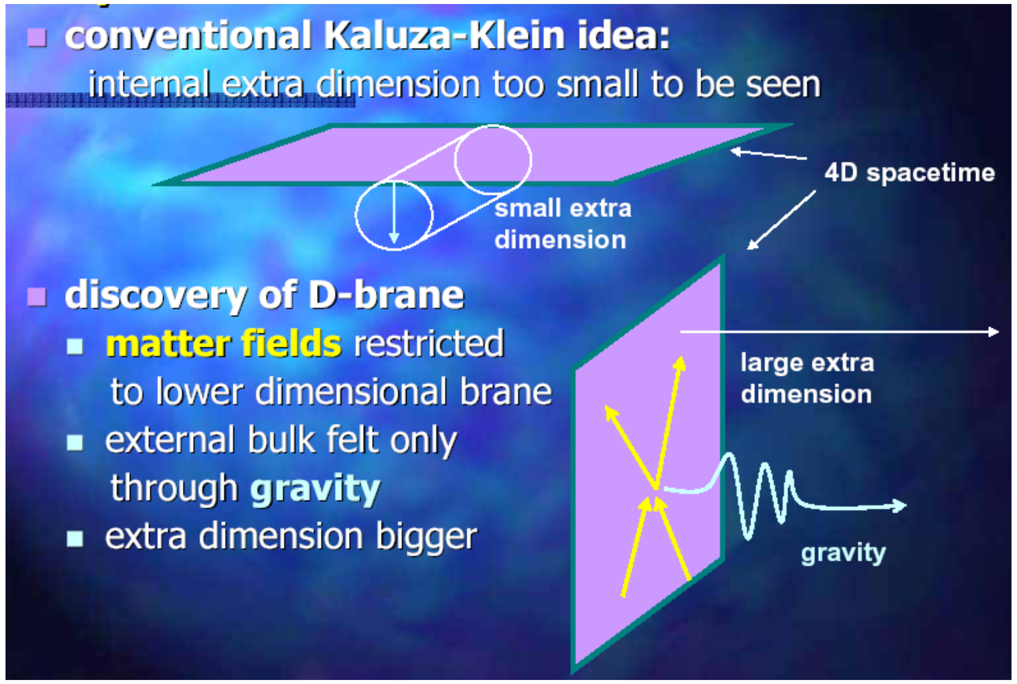

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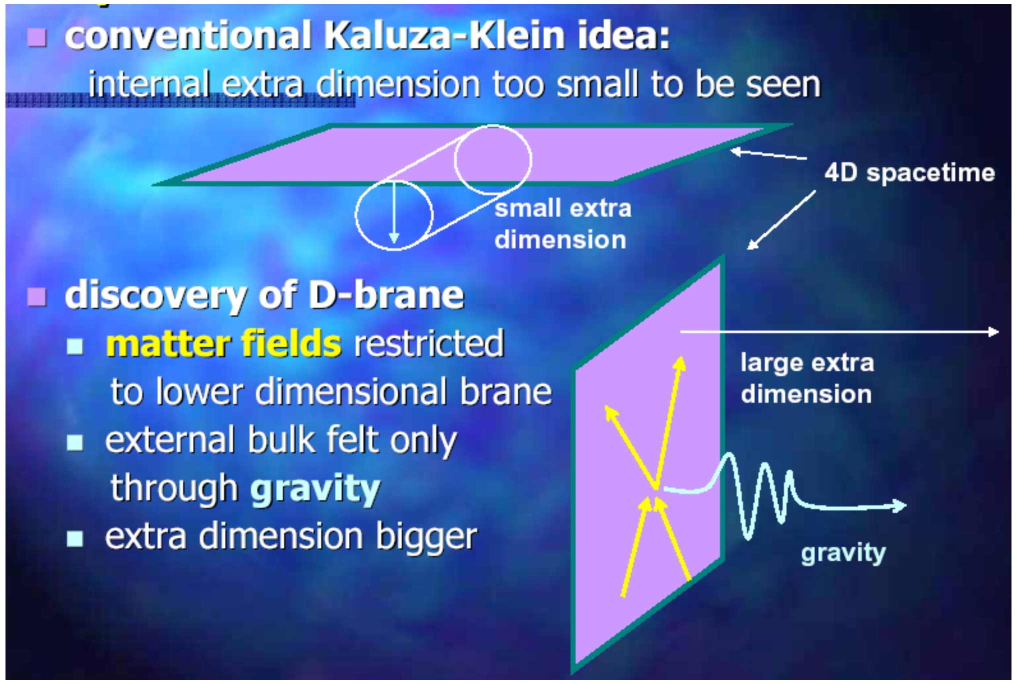

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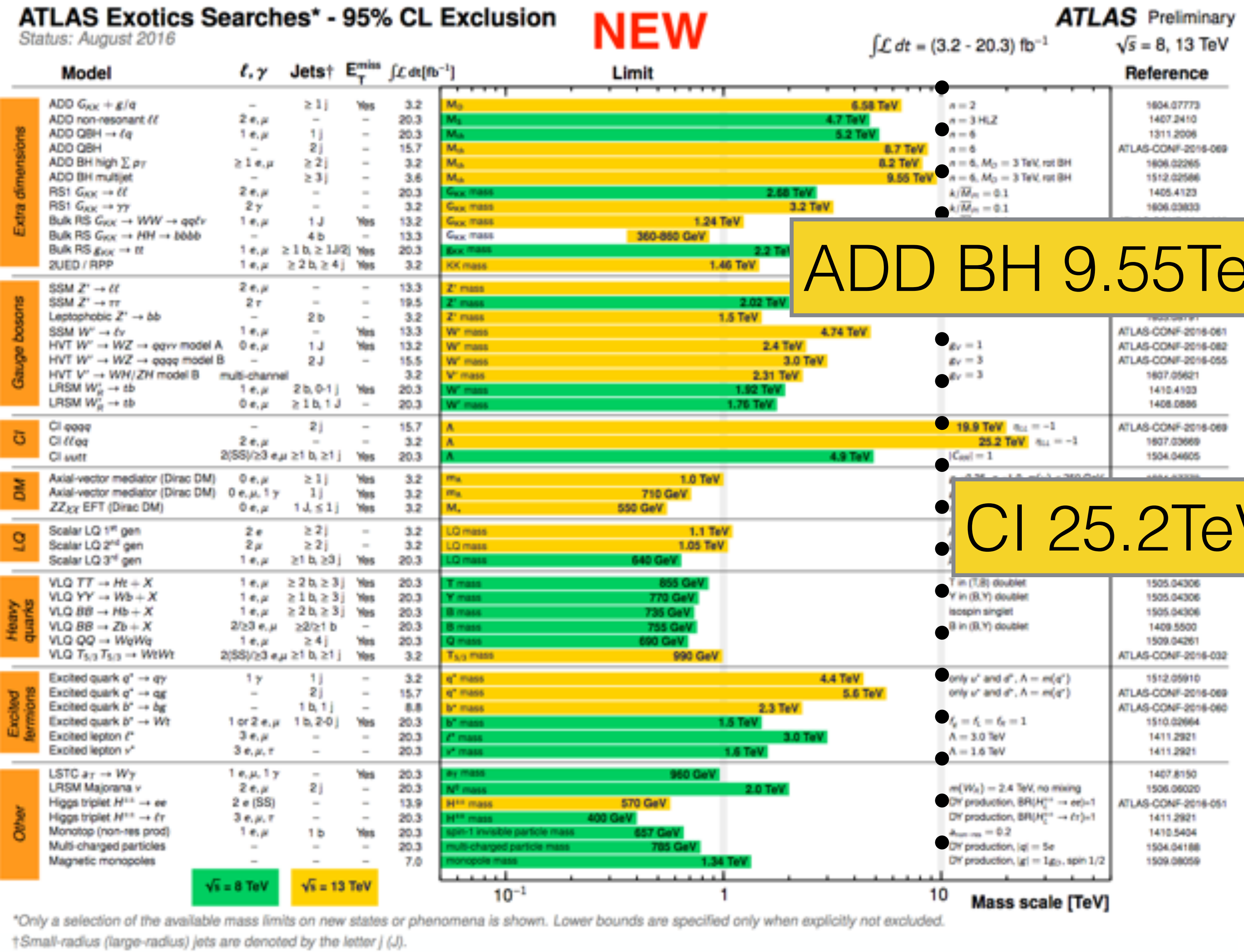
Drawback: No real motivation -> Unknown scale

Resonance search summary

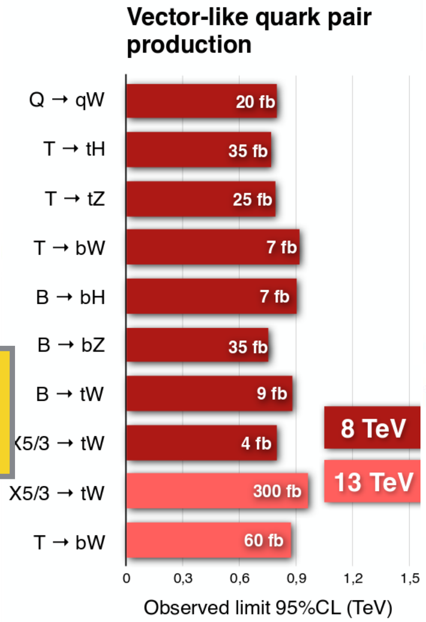
- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2

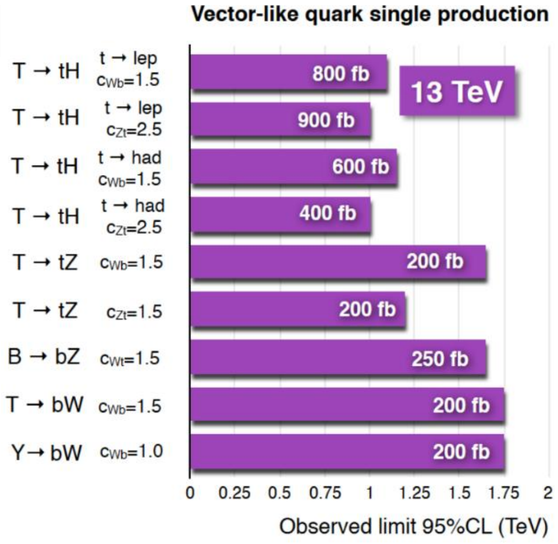


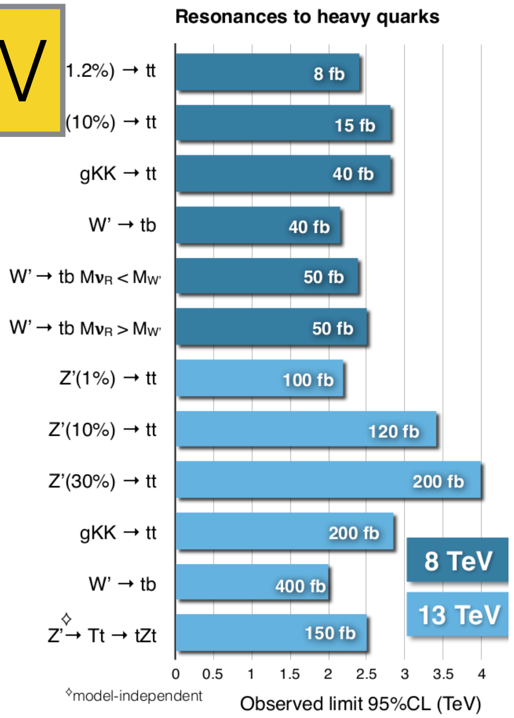
ADD BH 9.55TeV

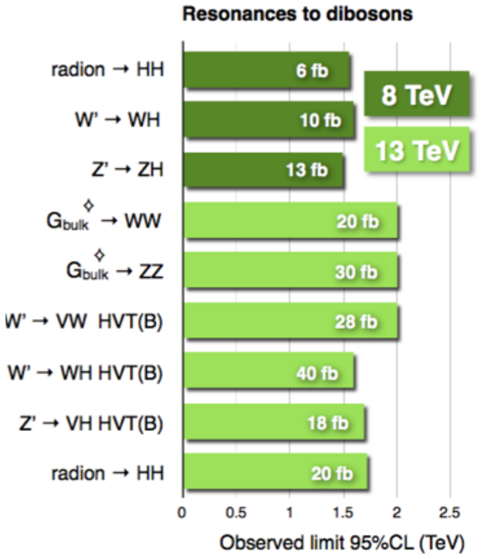
CI 25.2TeV

10TeV





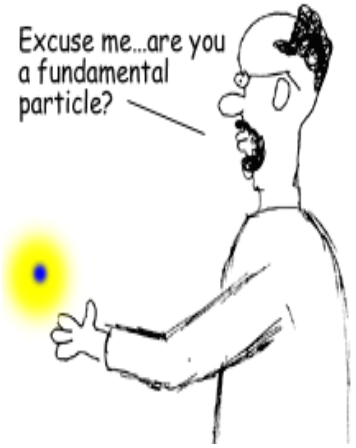




Search for New Physics

Compositeness

New level of fundamental particles



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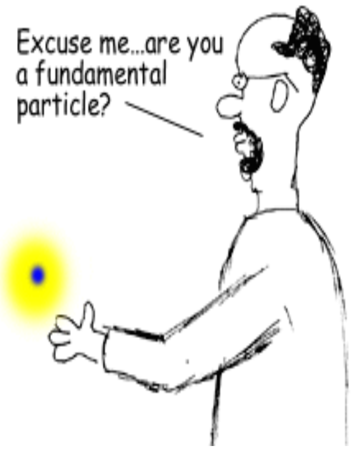
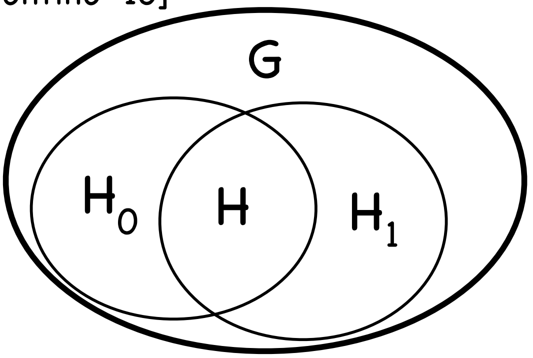
Compositeness



New level of fundamental particles

Higgs boson -> pseudo Numbu-Goldstone boson

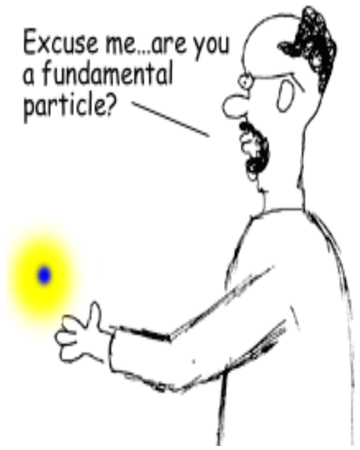


[Contino '10]

Global symmetry G
broken to H of SM

Search for New Physics

Compositeness



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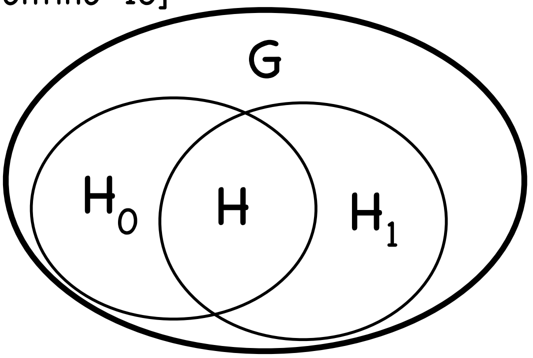
[Contino '10]



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Search for New Physics

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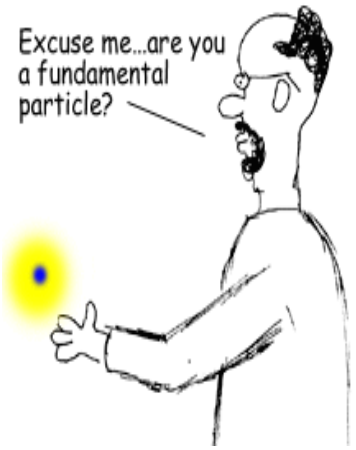

New level of fundamental particles

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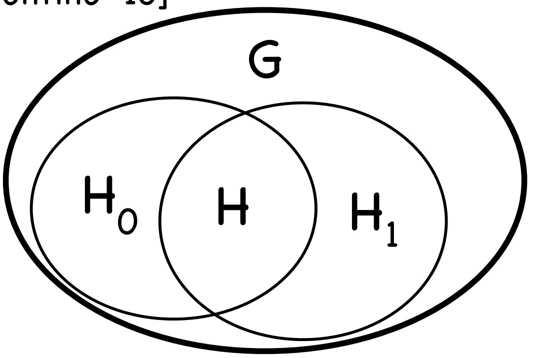

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Should be

$$\pi', \pi'', \rho', \rho'', \ldots$$

Search for New Physics

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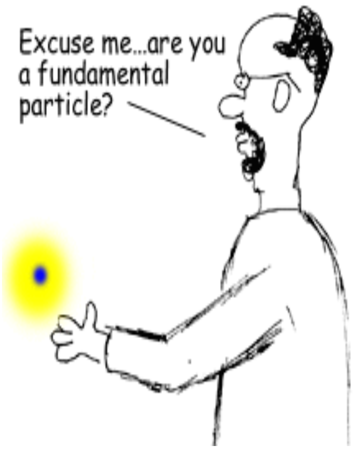

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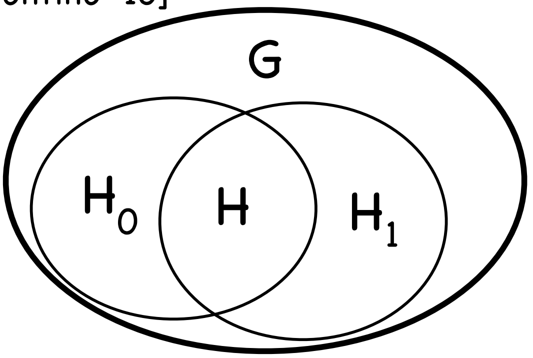

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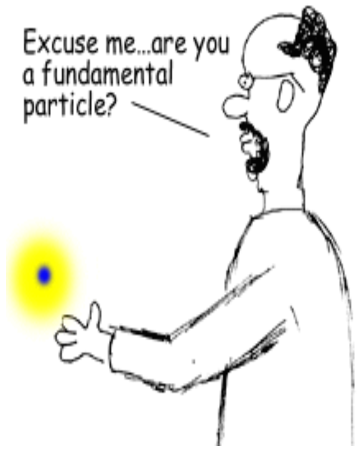
Advantage: No artificial scalar field

Protection from high energy physics

Search for New Physics

Compositeness



New level of fundamental particles

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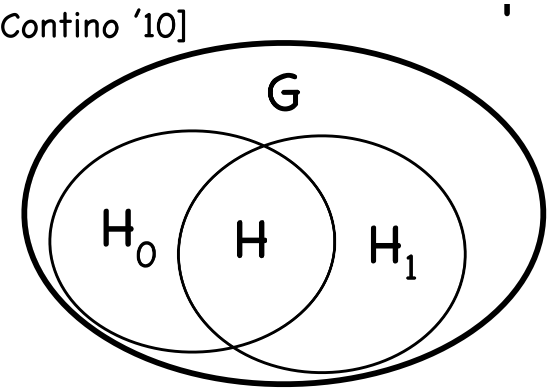
Quarks and Leptons made of preons



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Protection from high energy physics

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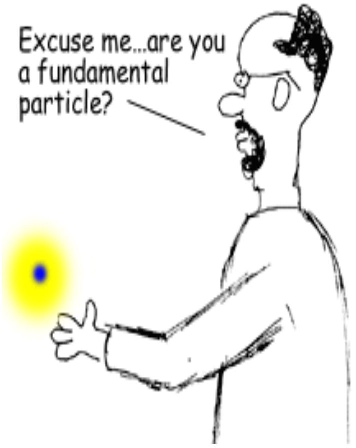

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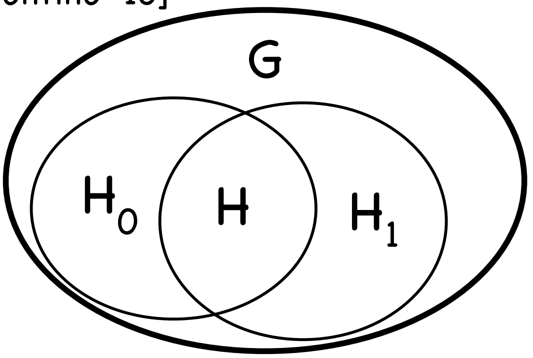

Global symmetry G

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Quarks and Leptons made of preons

New strong confining forces

$$Higgs\ boson \Leftrightarrow \pi - meson$$

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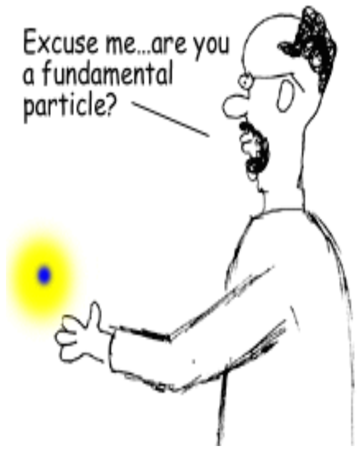
Protection from high energy physics

Search for New Physics

Compositeness



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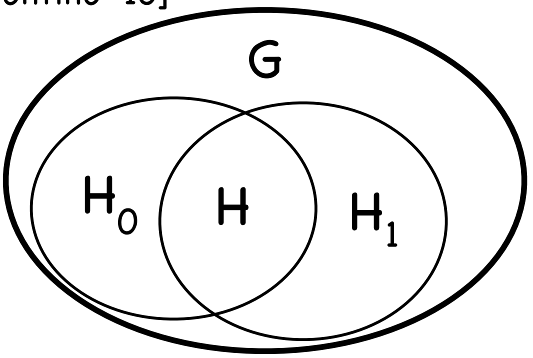

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Quarks and Leptons made of preons

↓

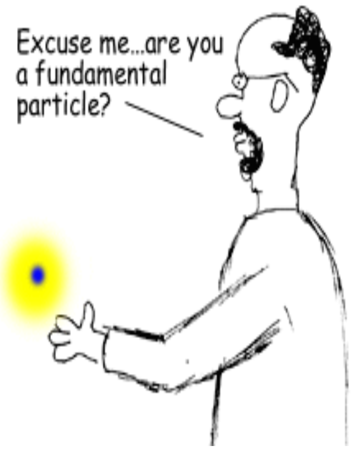
New strong confining forces

Technicolor
Walking Technicolor
Extended Technicolor
…

Advantage: No artificial scalar field
Protection from high energy physics

Search for New Physics

Compositeness



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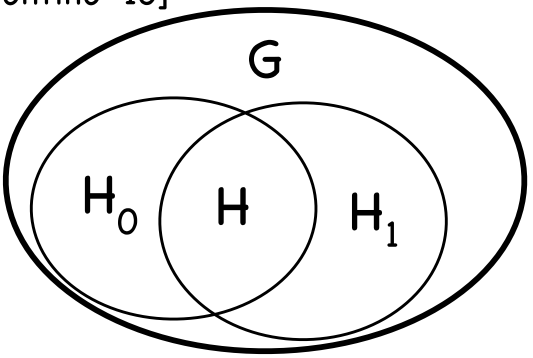

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- No new excited states observed

Search for New Physics

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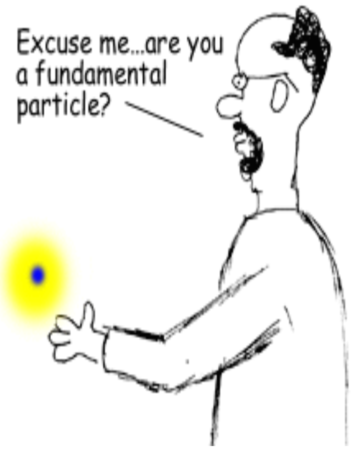

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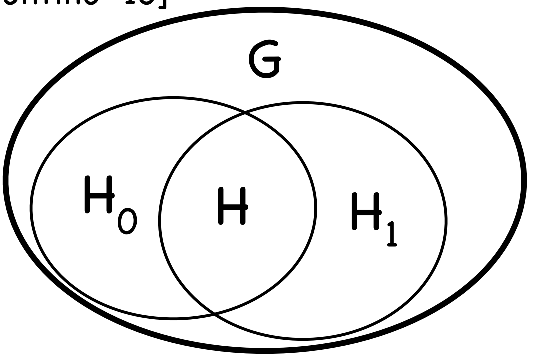

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⇓

New strong confining forces

Technicolor
Walking Technicolor
Extended Technicolor
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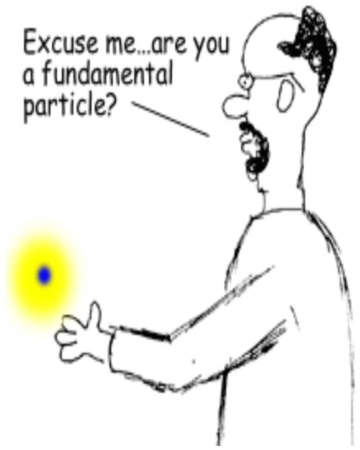
- No new excited states observed
- Problems with precision EW observables

Search for New Physics

Compositeness



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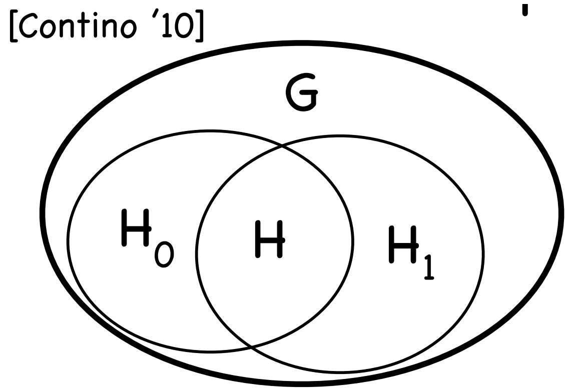

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Search for New Physics

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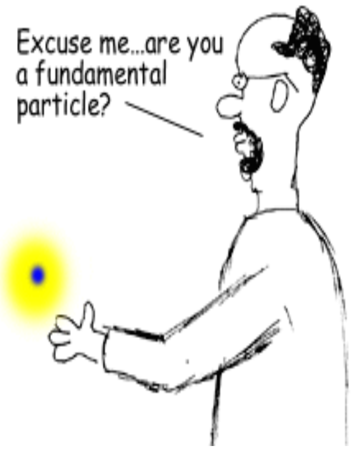

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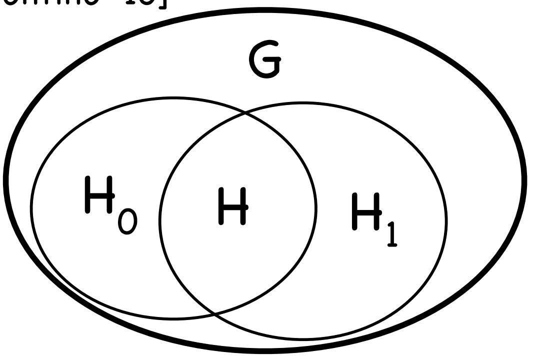

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⇩

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Still possible

Concluding Remarks

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☑ LHC experiments are at the front line of mystery land: be patient

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Concluding Remarks

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Concluding Remarks

- ☑ LHC experiments are at the front line of mystery land: be patient
- ☑ Target #1: Higgs sector
- ☑ Target #2: Dark Matter

Concluding Remarks

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I bet that discoveries will come!