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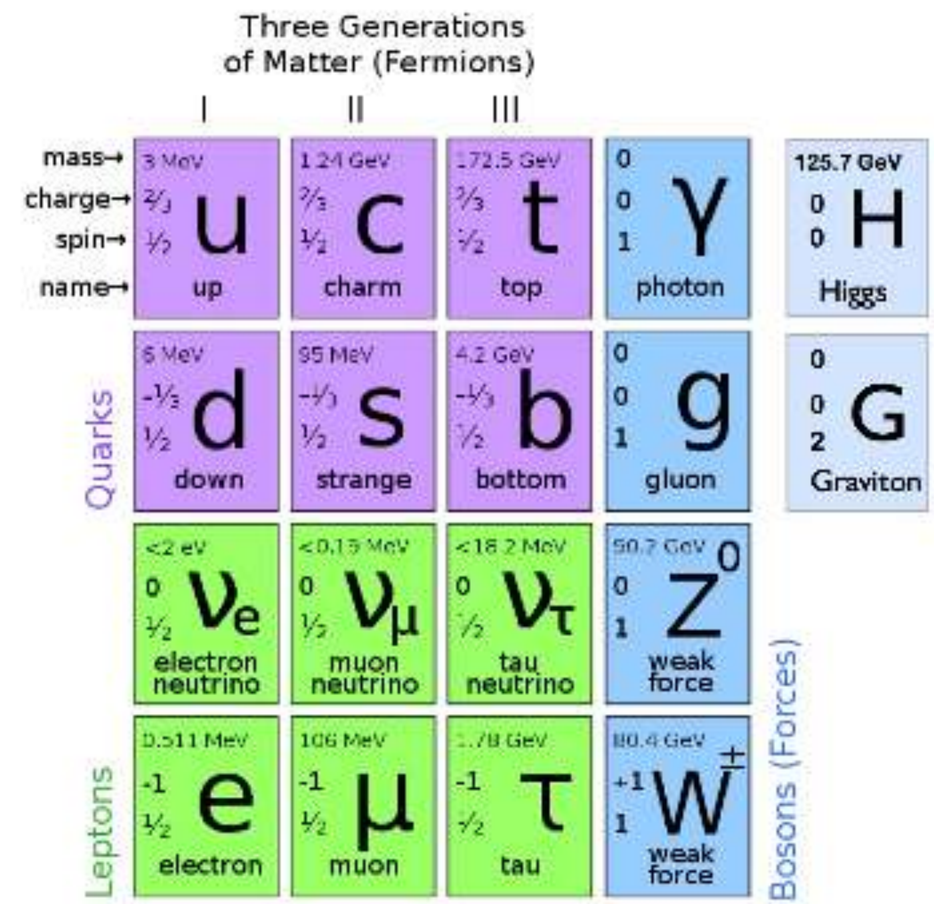
BOGOLIUBOV LABORATOTY FORT THEORETICAL PHYSICS

JOINT INSTITUTE FOR NUCLEAR RESEARCH

IN WAITING FOR NEW PHYSICS

THE PRINCIPLES

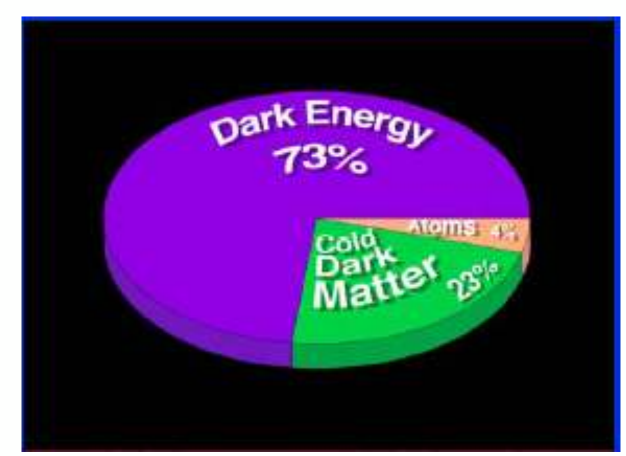


<u>The SM of today</u>:

- All particles are discovered
- All symmetries are confirmed
- The mechanism of spontaneous EW symmetry breaking is established
- Essentially all phenomena in particle physics are described by the SM
- All parameters are measured

The main loop-holes of the SM today:

- Bottom line of neutrino masses
- Nature of neutrino (Dirac or Majorana)



- Dark Matter is not a part of the SM
- What is it?

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs},$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu}$$
$$+i\overline{L}_\alpha\gamma^\mu D_\mu L_\alpha + i\overline{Q}_\alpha\gamma^\mu D_\mu Q_\alpha + i\overline{E}_\alpha\gamma^\mu D_\mu E_\alpha$$
$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha + i\overline{D}_\alpha\gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger(D_\mu H),$$

$$\boxed{+i\overline{N}_\alpha\gamma^\mu\partial_\mu N_\alpha}$$

possible right handed neutrino ?

$$\mathcal{L}_{Yukawa} = -y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H + y^D_{\alpha\beta}\overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta}\overline{Q}_\alpha U_\beta\tilde{H} + h.c.,$$

$$\boxed{+y^N_{\alpha\beta}\overline{L}_\alpha N_\beta\tilde{H}}$$

$$\mathcal{L}_{Higgs} = -V = m^2H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

All these parameters are not predicted by the SM and determined experimentally

Three gauge couplings

Three or four Yukawa matrices

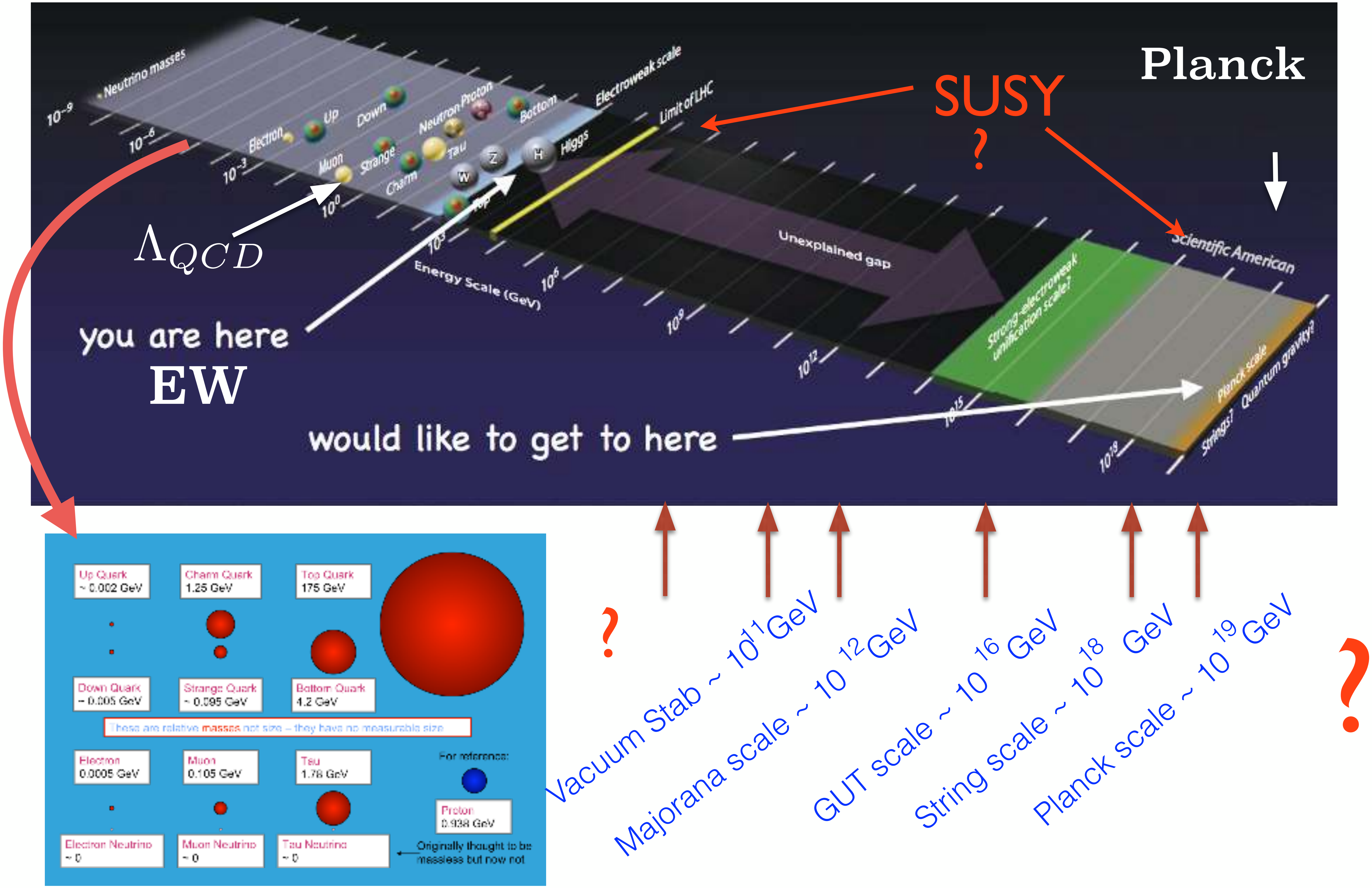
Two parameters

THE OPEN QUESTIONS

- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how to calculate the hadron matrix elements?
- what defines the spectrum and mixings?
- how CP violation occurs in the Universe?
- how the baryon asymmetry appears?

- Is it self consistent ?
- Does it describe <u>all</u> experimental data?
- Are there <u>any</u> indications for physics beyond the SM?
- Is it compatible with Cosmology? Where is dark matter?

IS THERE ANOTHER SCALE EXCEPT FOR EW AND PLANK?



Fabio Zwirner, EPS HEP 2017

We live in data driven era and need an experimental hint to proceed

THE WAYS BEYOND

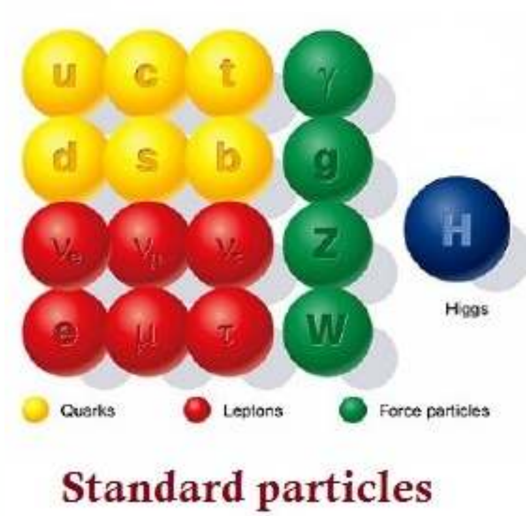
- Extension of symmetry group of the SM : SUSY, GUT, new U(1)'s
  -> may solve the problem of Landau pole, the problem of stability, the hierarchy problem, may give the DM particle
- Additional particles: Extra generations, extra gauge bosons, extra Higgs bosons, extra neutrinos, etc
  -> may solve the problem of stability, DM
- New fundamental objects (compositeness)
- Extra dimensions: Compact or flat extra dim
  -> Opens a whole new world of possibilities, may solve the problem of stability and the hierarchy problem, gives new insight into gravity
- New paradigm beyond local QFT: string theory, brane world, etc
  -> main task is unification with gravity and construction of quantum gravity

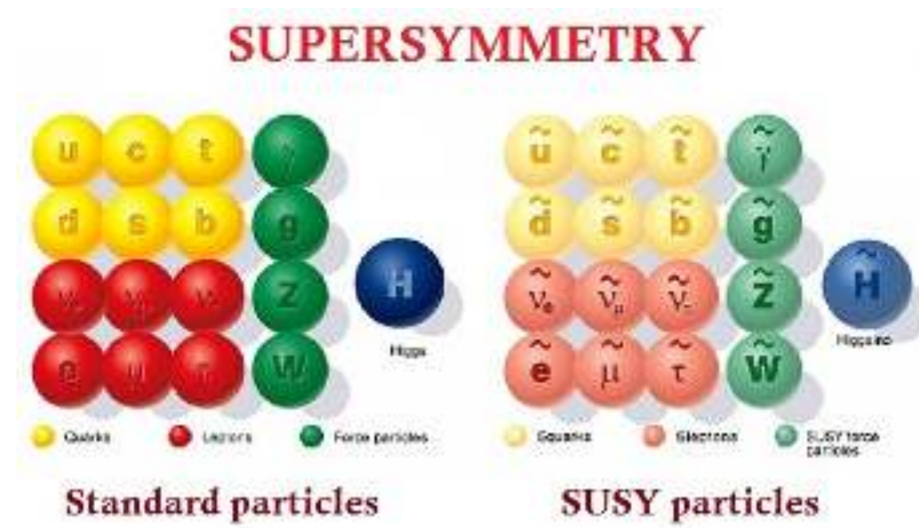
NEW SYMMETRIES

SUPERSYMMETRY

Supersymmetry is an extension of the Poincare symmetry of the SM

Supersymmetry is a unique possibility to unify particles with different spin





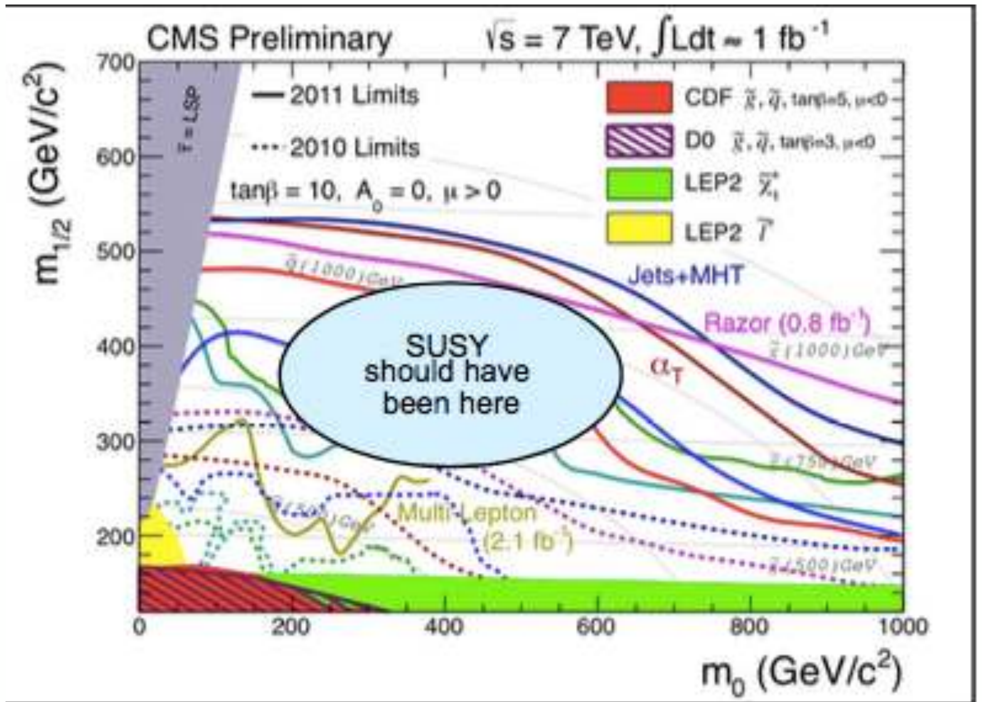
Supersymmetry remains, to this date, a well-motivated, much anticipated extension to the Standard Model of particle physics

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

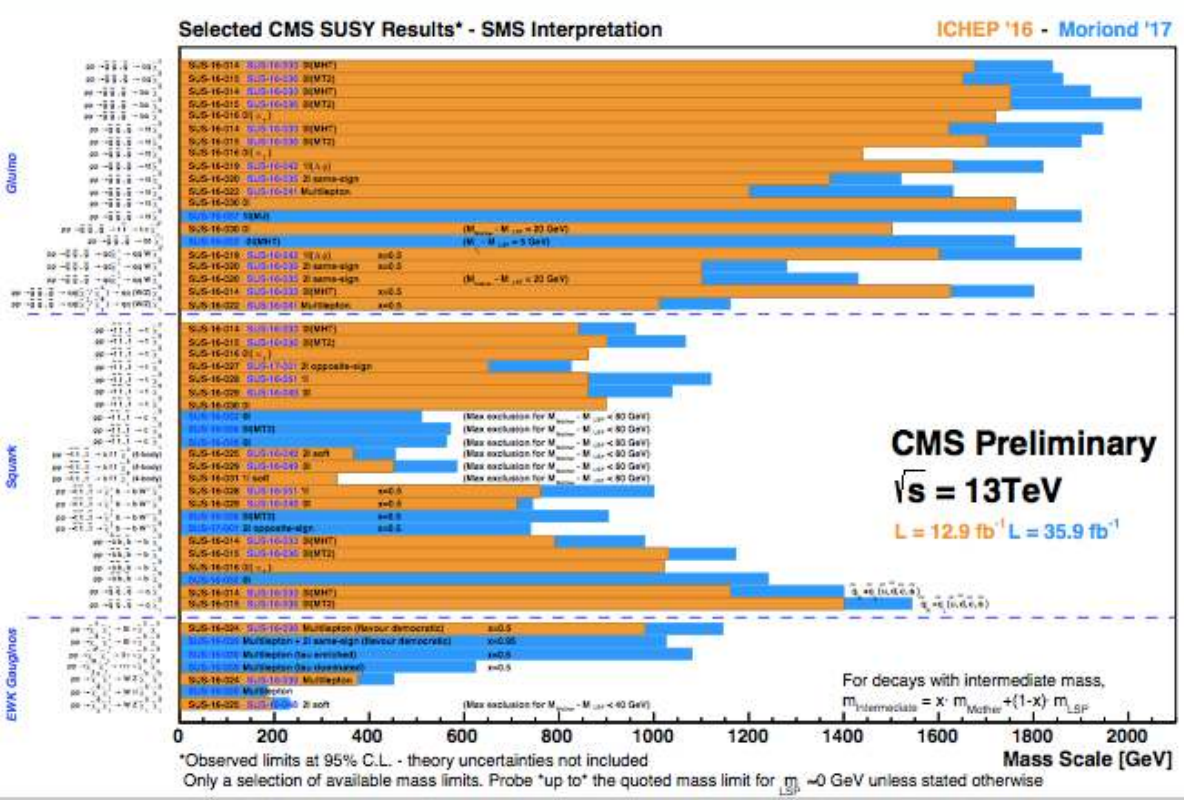
NEW SYMMETRIES

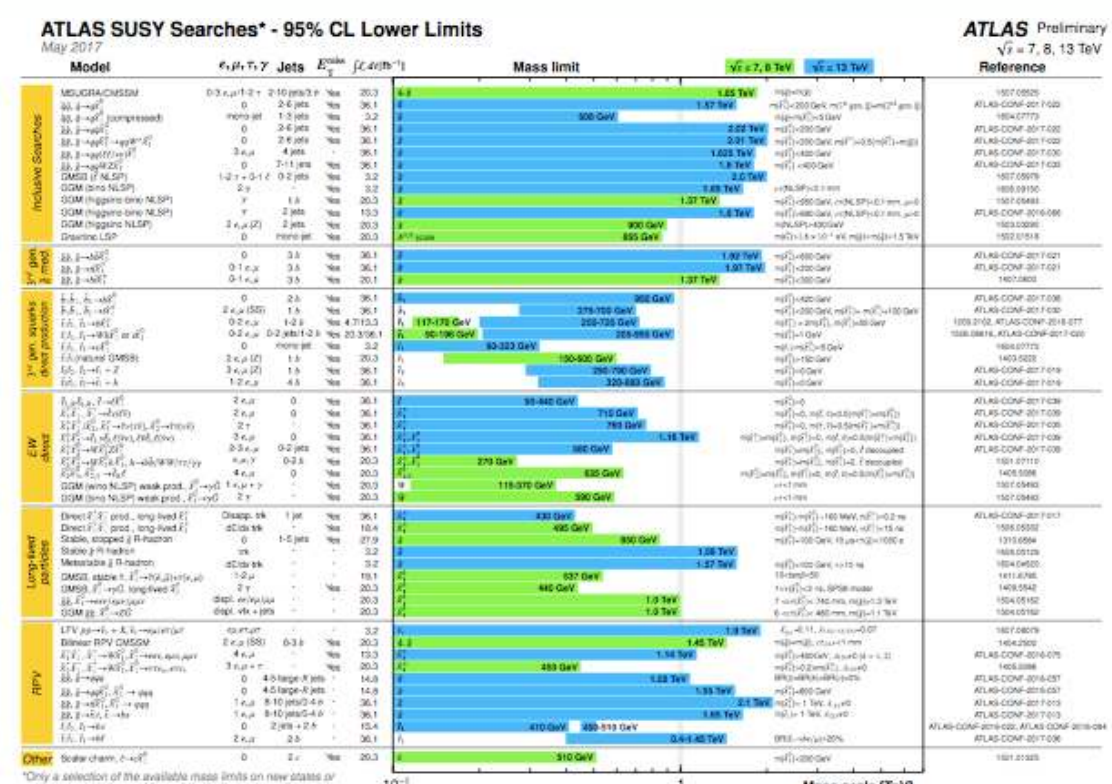
SUPERSYMMETRY

Paris Sphicas, EPS HEP 2017



- Low energy Supersymmetry is on stake
- If we do not see it on LHC the low energy motivation fades away
- One can still avoid exclusion of SUSY but the price is more sophisticated models



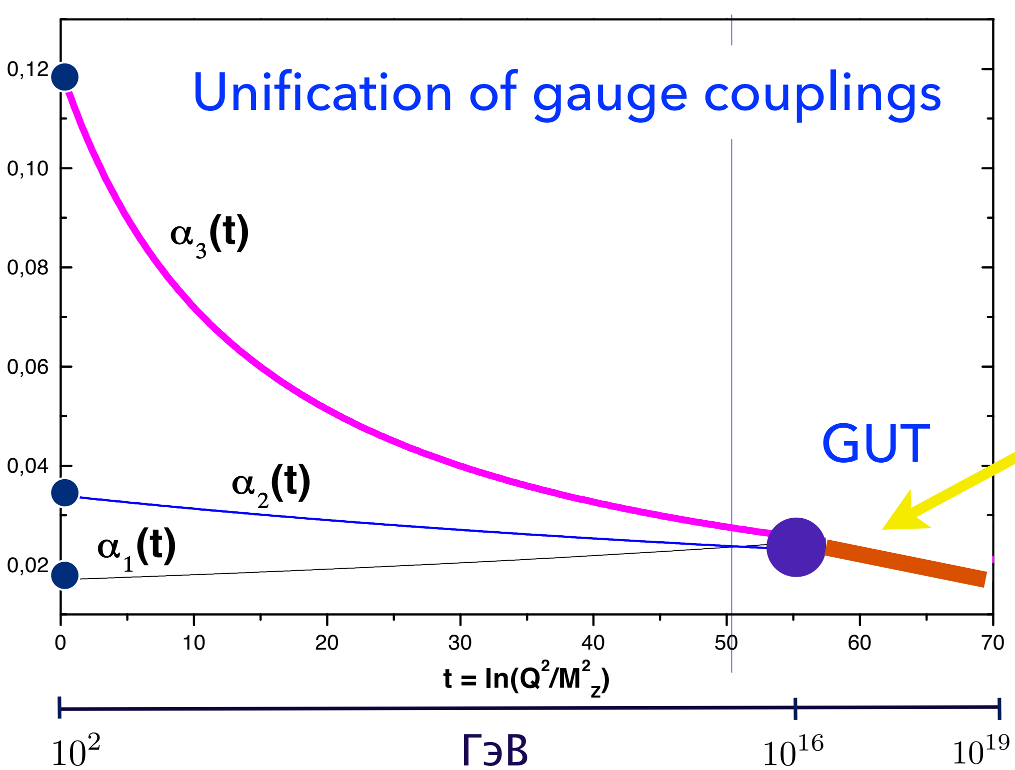


NEW SYMMETRIES

GRAND UNIFICATION

Grand Unification is an extension of the Gauge symmetry of the SM

$$
\begin{array}{cccccl}
 & \text{Low energy} & & \Rightarrow & \text{High energy} \\
SU_c(3)\otimes & SU_L(2)\otimes & U_Y(1) & \Rightarrow & G_{GUT} \quad (or\ G^n + \text{discrete symmetry}) \\
\text{gluons} & W, Z & \text{photon} & \Rightarrow & \text{gauge bosons} \\
\text{quarks} & \text{leptons} & & \Rightarrow & \text{fermions} \\
g_3 & g_2 & g_1 & \Rightarrow & g_{GUT}
\end{array}
$$



$$SU(3) \times SU(2) \times U(1) \subset G_{GUT}$$

$$Ex: SU(5), SO(10), E(6), SU(5) \times U(1),$$
$$SU(4) \times SU(2) \times SU(2), SO(10) \times U(1)$$

GRAND UNIFICATION

Solves many problems of the SM:

- absence of Landau pole
- Decreases the number of parameters
- All particles in a single representation (**16** of SO(10))
- Unifies quarks and leptons -> spectrum and mixings from «textures»
- A way to **B** and **L** violation

Creates new problems:

- Hierarchy of scales $M_W/M_G \sim 10^{-14}$
- Large Higgs sector is needed for GUT symmetry breaking

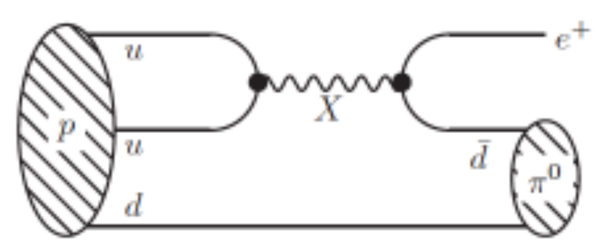
Crucial predictions:

- Proton decay $P \to e^+\pi, \quad P \to \bar{\nu}K^+$
- Neutron-antineutron oscillations
- $|\Delta(B-L)| = 1 \ (|\Delta(B-L)| = 2)$ processes

Unification of the gauge couplings and stabilization of the hierarchy mights require low energy SUSY

SUSY GUTS – Nucleon decay

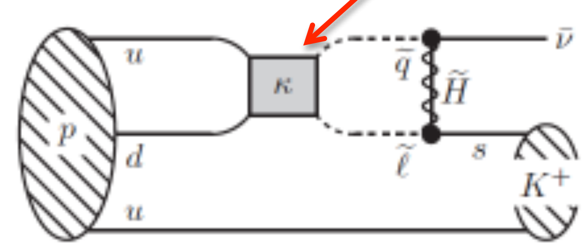
$\frac{1}{\Lambda} QQQL|_F$



(a) Dimension 6.

$p \to \pi^0 + e^+$

$\tau_{p\to e^+\pi^0} > 1\times 10^{34}$ yrs, $M_X > 10^{16}\,GeV$



(b) Dimension 5.

$p \to K^+ + \bar{\nu}$

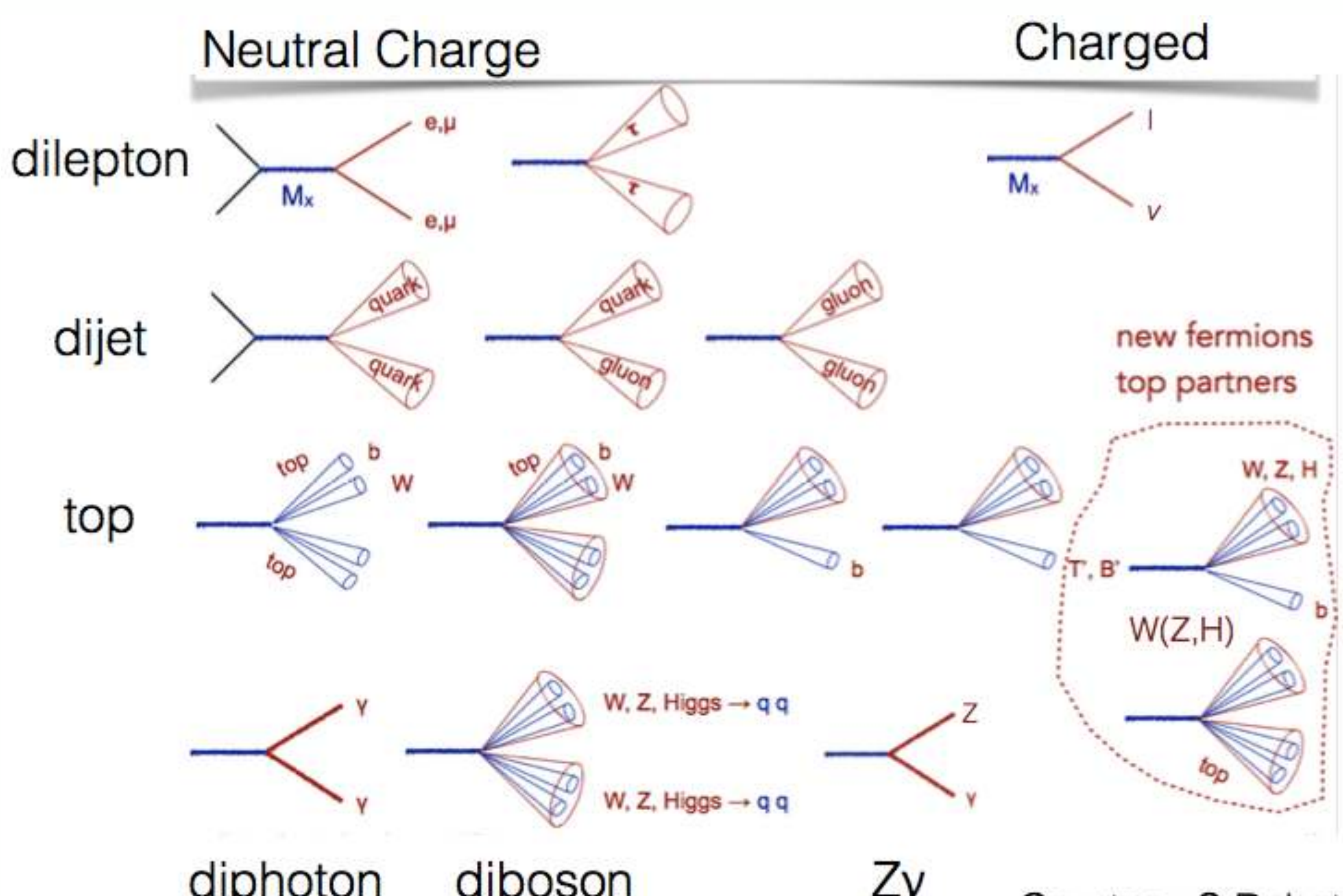
$\tau_{p\to K^+\bar{\nu}} > 3.3\times 10^{33}\,yrs$

NEW SYMMETRIES

EXTRA U(1)', SU(2)'

- Appear in some GUT models
- Inspired by string models

Used as possible BSM signal with energetic single jet or diet events



Courtesy S.Rahatlou

Used as possible Dark matter candidate - Dark photon

Mixture of a usual EM U(1) photon and a new U(1)' one

$$\mathcal{L} \sim F_{\mu\nu} F'^{\mu\nu}$$

Dedicated experiment to look for conversion of a usual photon into a dark one

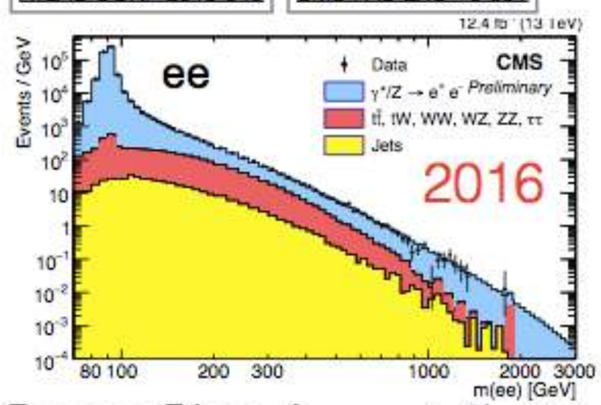
ADDITIONAL GAUGE BOSONS

Experiment

- Search for Z' (Di-muon events)
- Search for W' (single muon/ jets)
- Search for resonance decaying to t-tbar
- Search for diboson resonances
- Monojets + invisible

Same Flavor Opposite Sign (ee, μμ, ττ)

ATLAS-CONF-2016-045 CMS-PAS-EXO-16-031



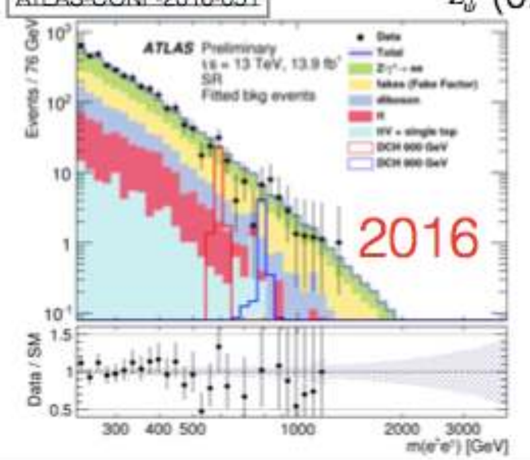
Same Sign (ee, μμ)

ATLAS-CONF-2016-051

Z'_{SSM}(3% width) >4 TeV

Z'_ψ (0.5% width) >3.36 TeV

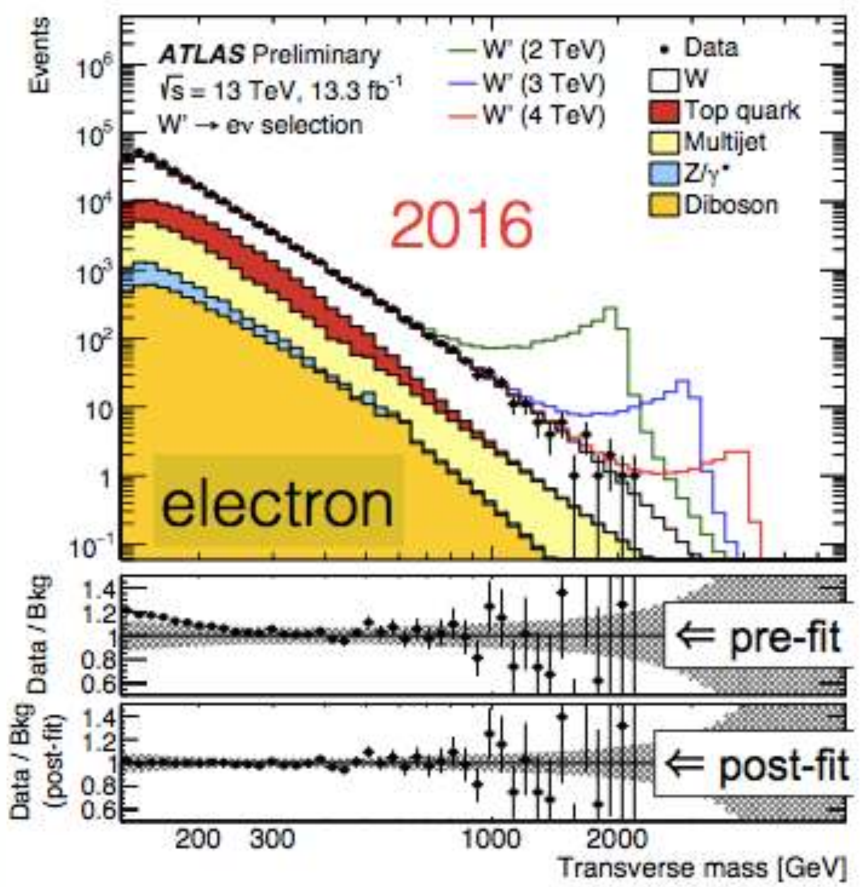
95% CL exclusion limit



$H_R^{\pm\pm}$ >420 GeV

$H_L^{\pm\pm}$ >570 GeV

ATLAS-CONF-2016-061 CMS-PAS-EXO-15-006



SSM W' >4.74 TeV

No indication so far - experimental limits on Z′ and W′ masses around few TeV

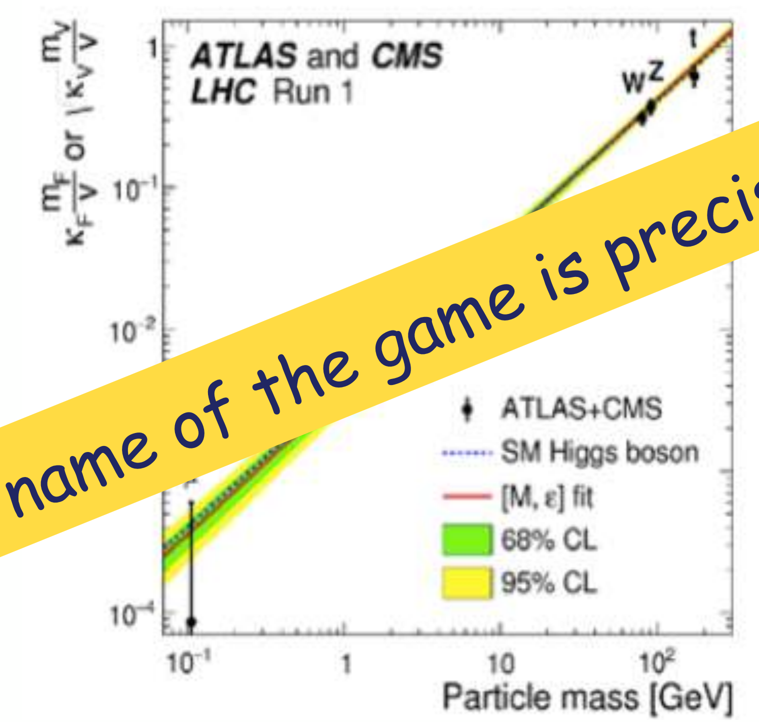
NEW PARTICLES

Is it the SM Higgs boson or not?

What are the alternatives?

How to probe?

- Probe deviations from the SM Higgs couplings



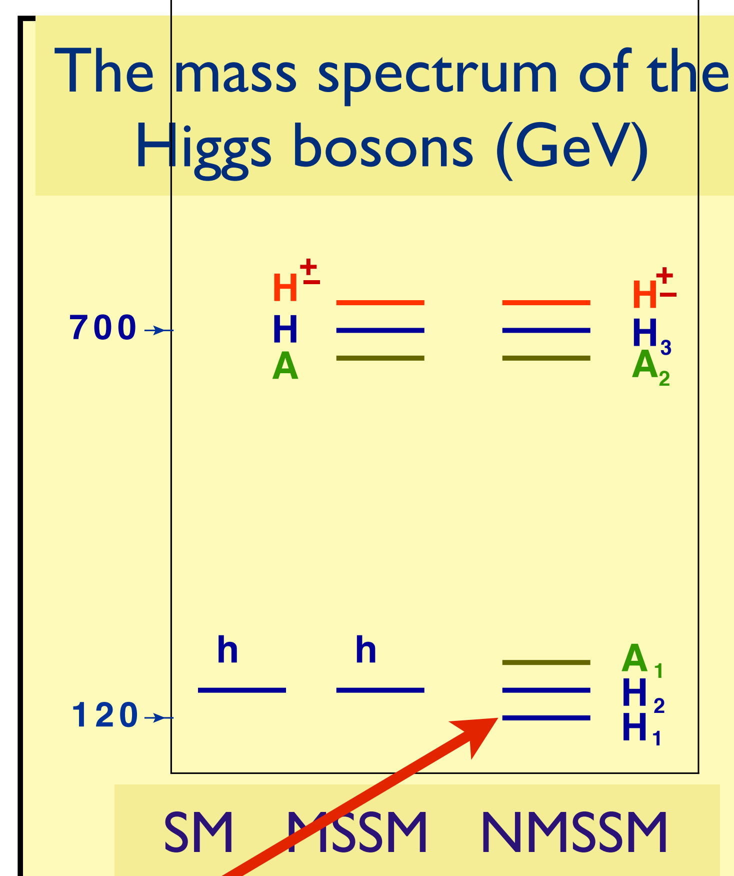
The name of the game is precision

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

EXTENDED HIGGS SECTOR

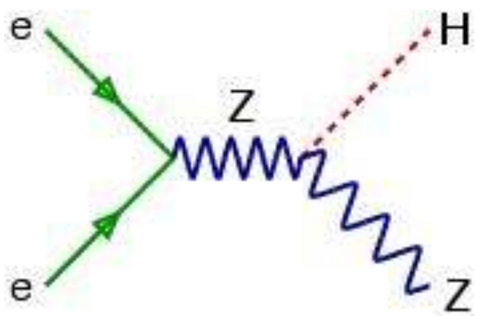
A. Singlet extension
B. Higgs doublet extension
C. Higgs triplet extension

- Perform direct search for additional scalars



We may have found one of these states

PRECISION PHYSICS OF THE HIGGS BOSONS

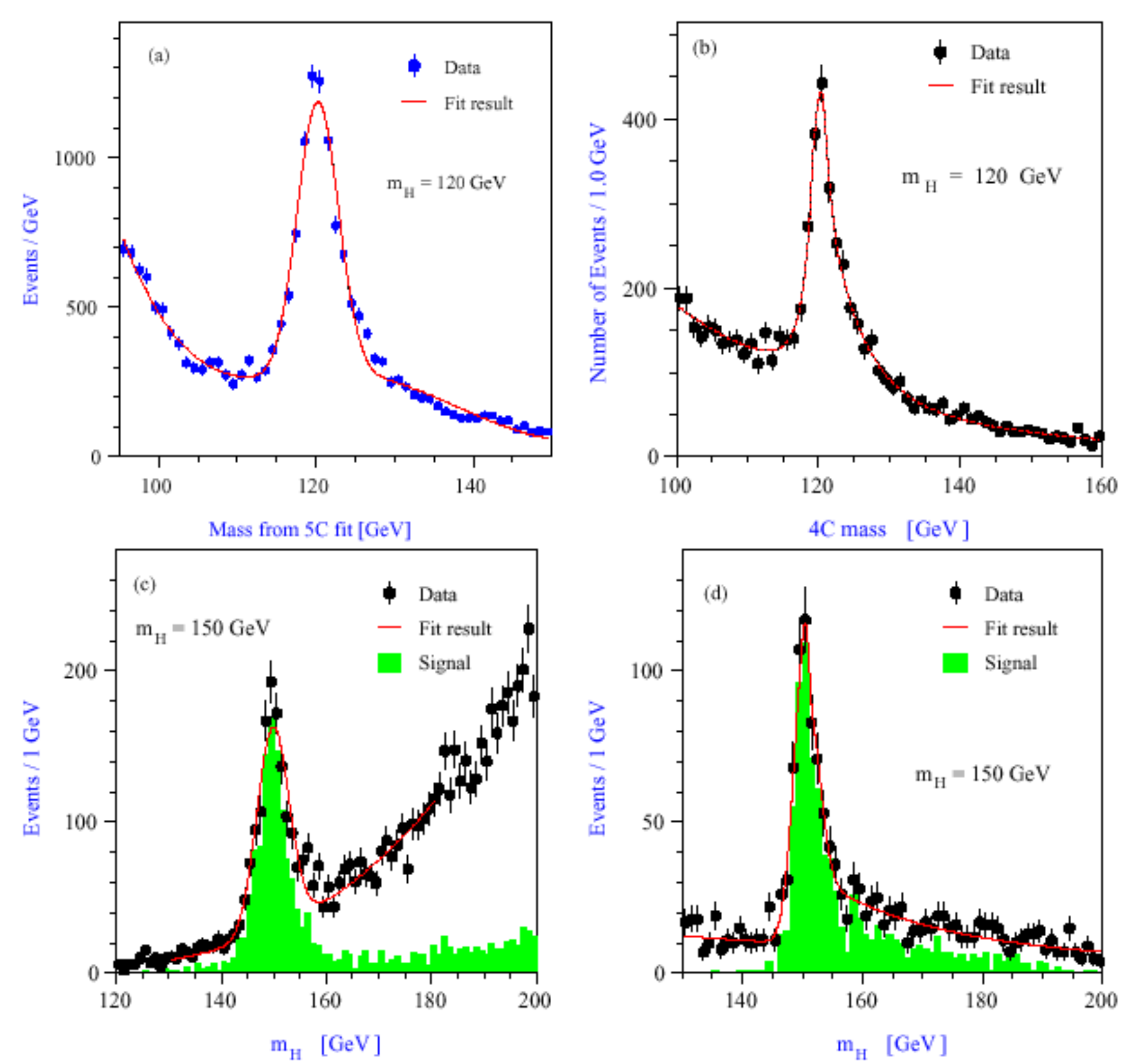


$\rightarrow b\bar{b}q\bar{q}$

ee -> HZ diff. decay channels

Int Linear Collider

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

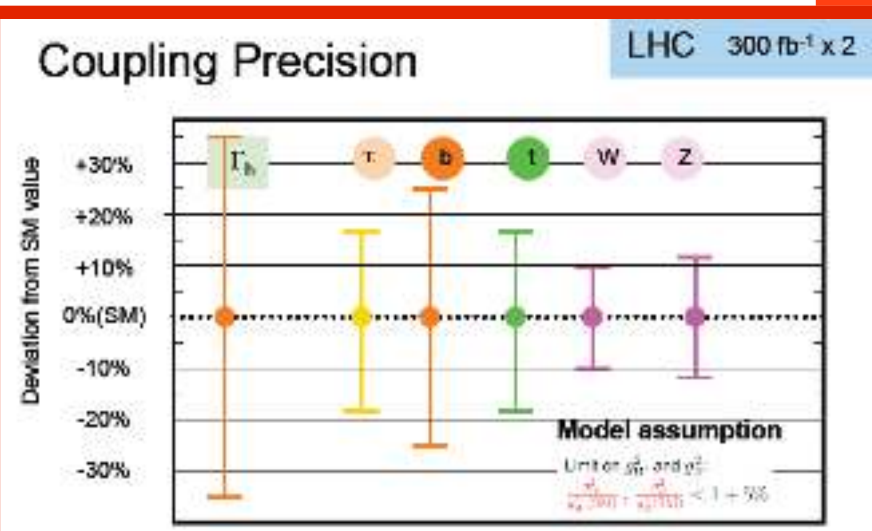


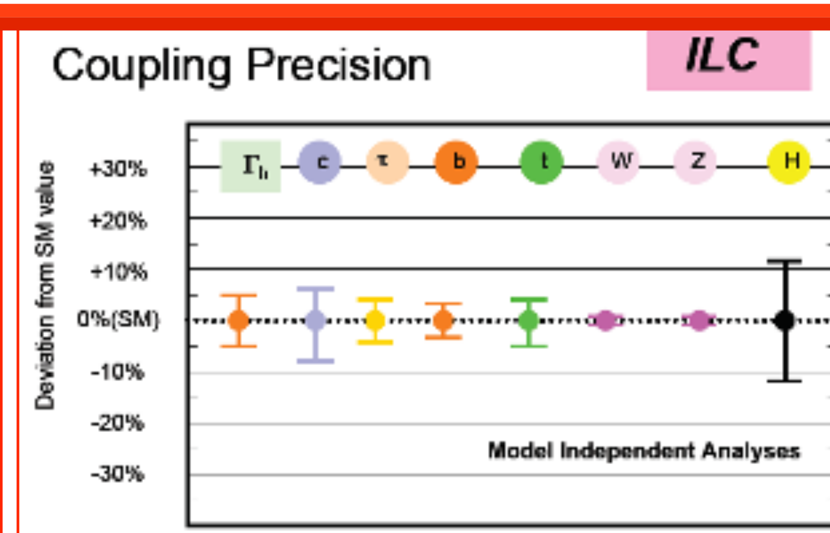
$\rightarrow q\bar{q}\ell^+\ell^-$

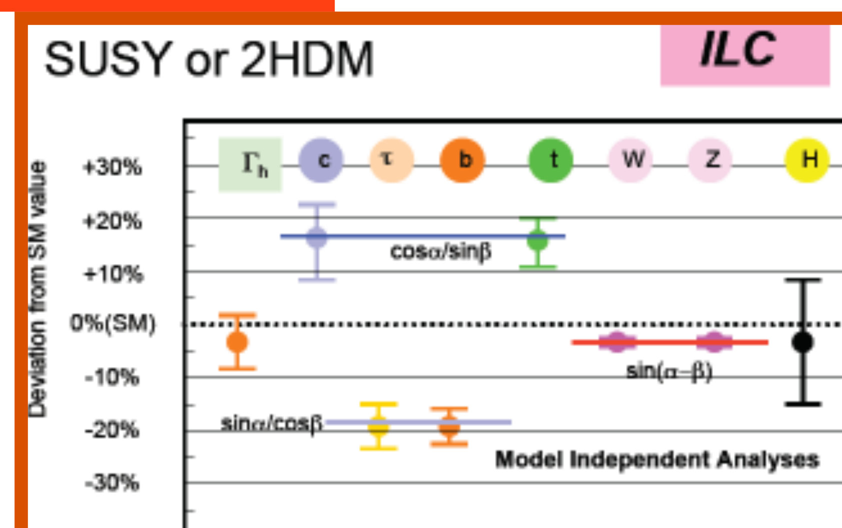
Δm_H = 40 MeV

$\rightarrow W^+W^-\ell^+\ell^-$

Δm_H = 70 MeV

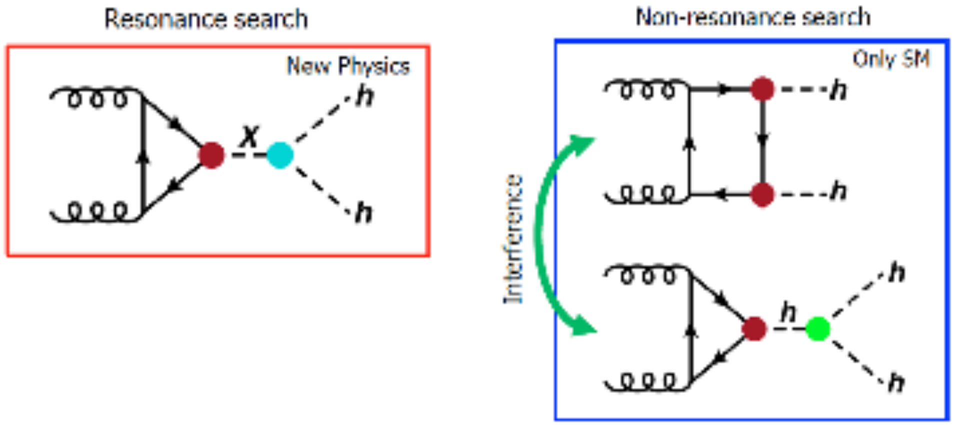




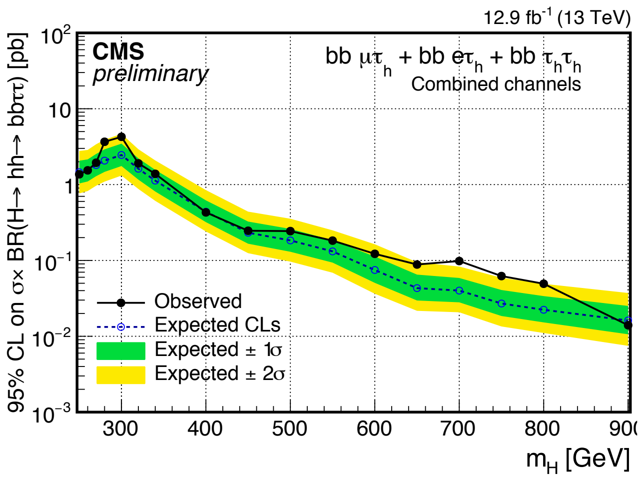


EXTRA HIGGS BOSONS

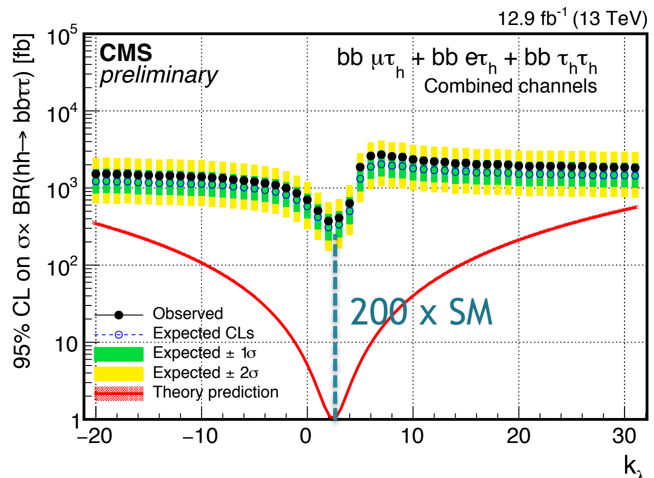
Higgs→hh→bbττ



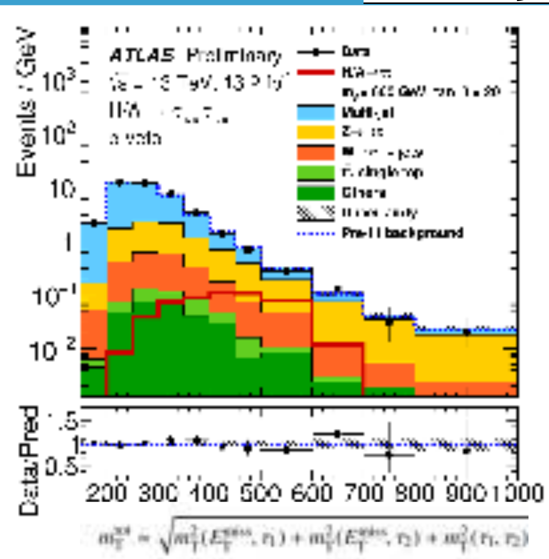
Resonant

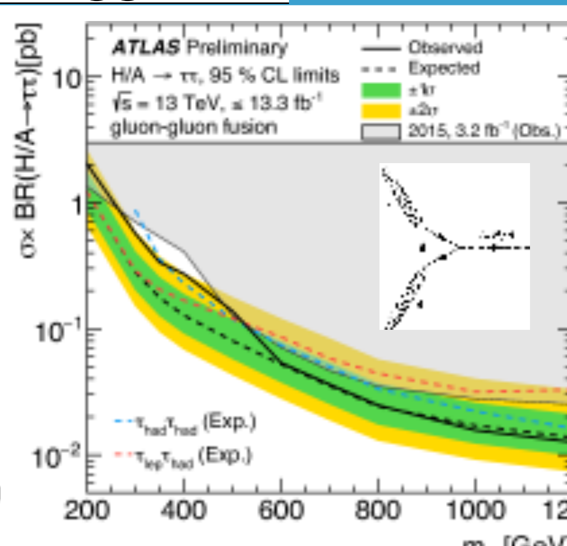


Non-Resonant

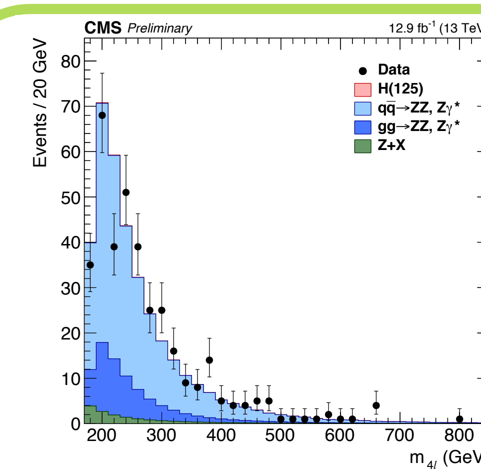


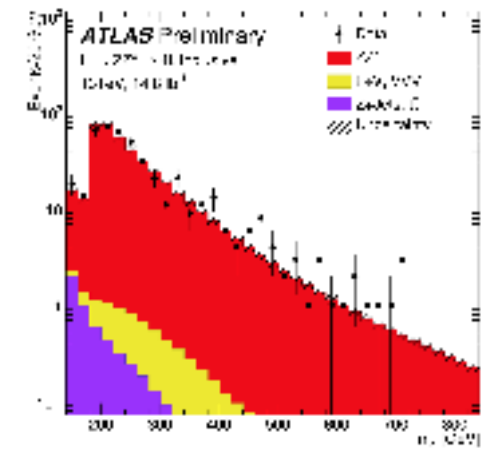
Heavy Higgs→ττ





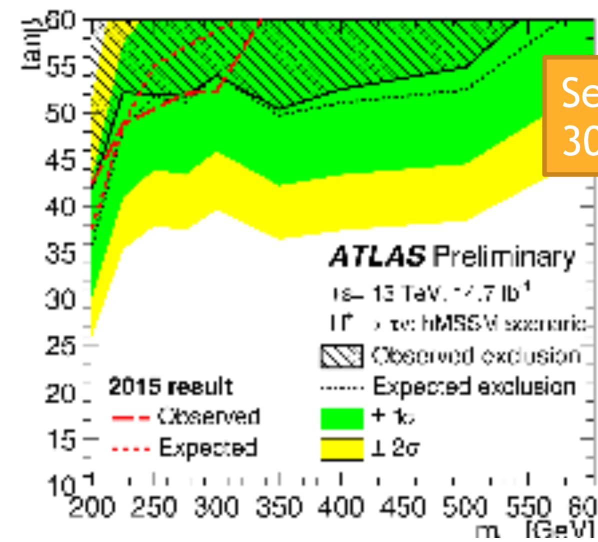
Heavy Higgs→ZZ→4l



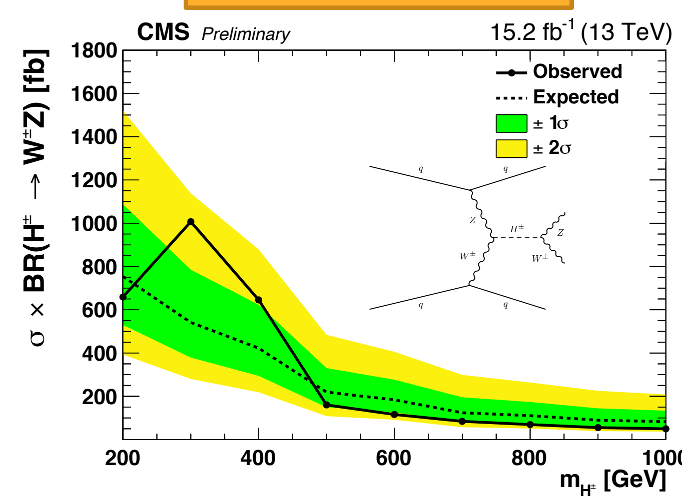


Charged Higgs

Search for H±→tb
300<$m_{H^\pm}$<1000 GeV



Search for H±WZ



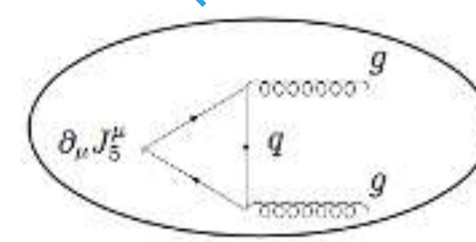
NEW PARTICLES AXION OR AXION-LIKE PARTICLES

Javier Redondo, EPS HEP 2017

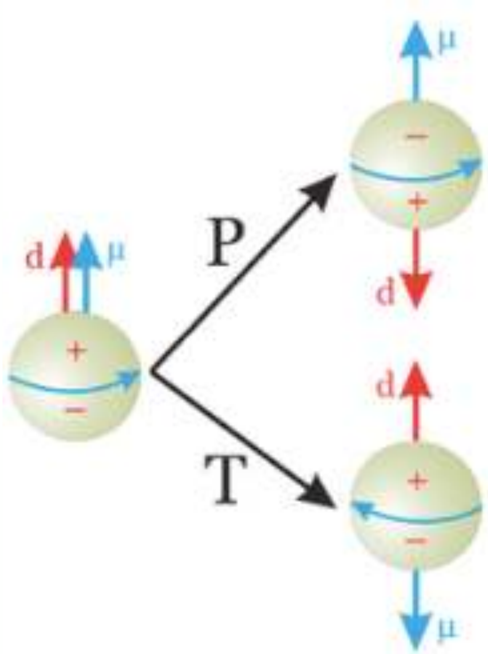
- CP violation in QCD sector: CKM angle $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ AND flavour-neutral phase $\theta = \theta_{\rm QCD} + N_f \delta$

$$\mathcal{L}_{\rm SM} \ni -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$

Axial anomaly



The θ-angle produces flavour-neutral CP violation like Electric Dipole Moments



- **Neutron EDM** (Guo 1502.02295)

$$d_n = -4 \times 10^{-3} \times \theta\ [\mathrm{e\,fm}]$$

- **Experimental upper limit** (Grenoble hep-ex/0602020)

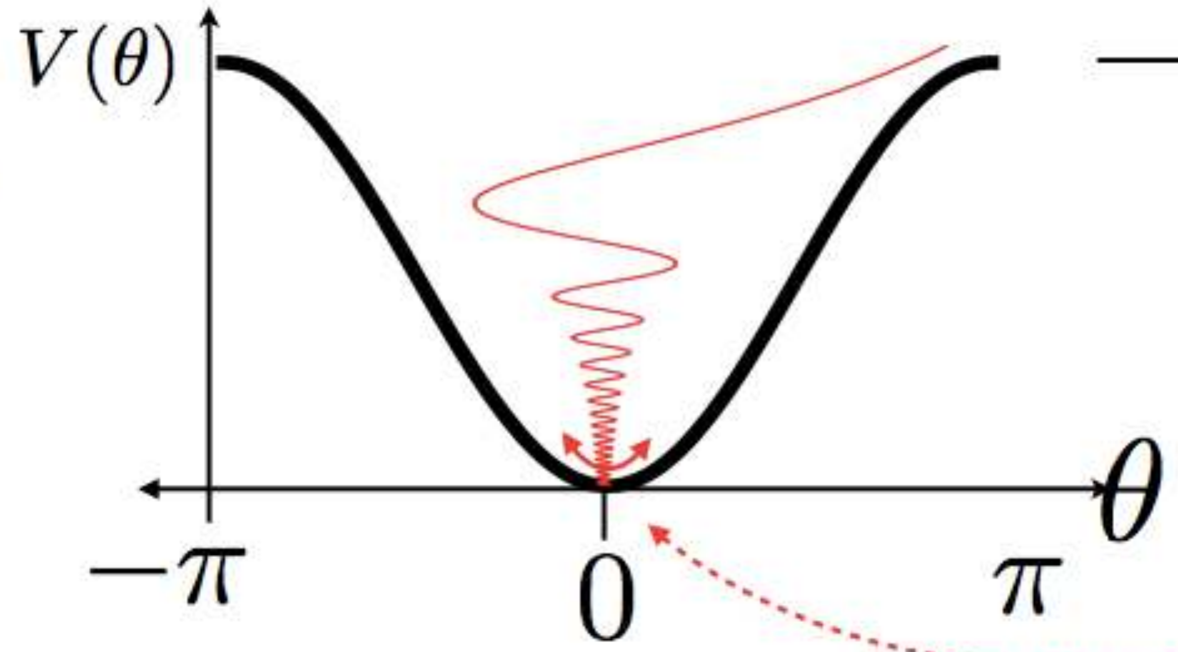
$$|d_n| < 3 \times 10^{-13}\ [\mathrm{e\,fm}]$$

- **Why is $\theta < 10^{-10}$?**

PECCEI-QUINN MECHANISM - AXION

- Any theory promoting θ to a dynamical field, $\theta(t, \mathbf{x})$, will dynamically set $\theta \to 0$ after some time...

Potential energy density



→ generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: Global U(1) axial symmetry, spontaneously broken, colour anomalous -> Goldstone boson

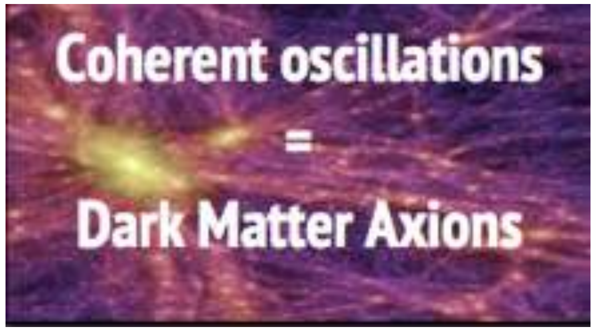
$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta$$

New Spontaneous symmetry breaking [energy] scale f_a

Canonically normalised θ field is the QCD AXION! $a(x) = \theta(x) f_a$

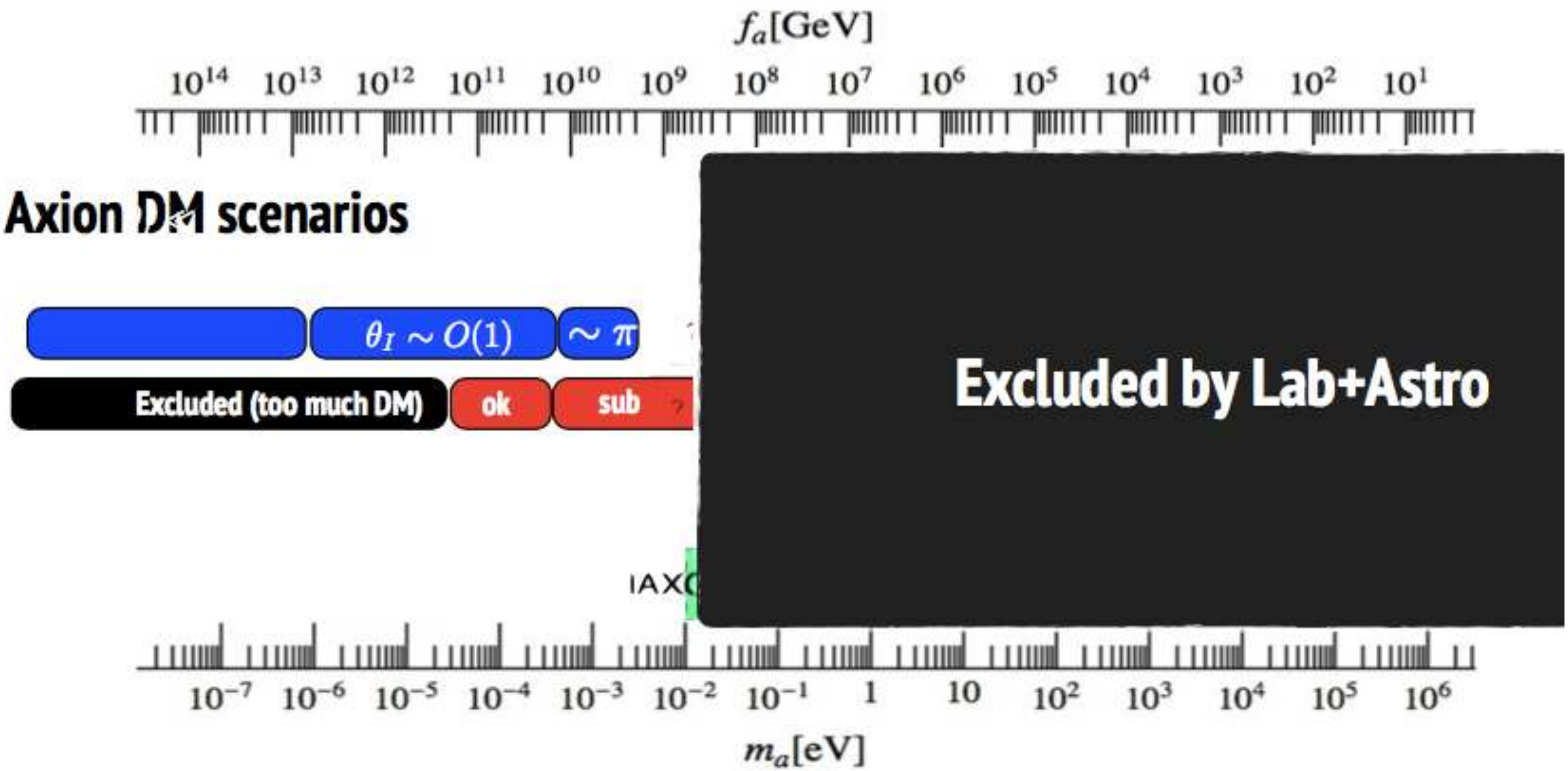
WW Axion

WHAT IS THE MASS TO GET $\Omega_{CDM}h^2 = 0.12$?



- Some amount of axion Dark matter is unavoidable!

- Axion DM scenarios



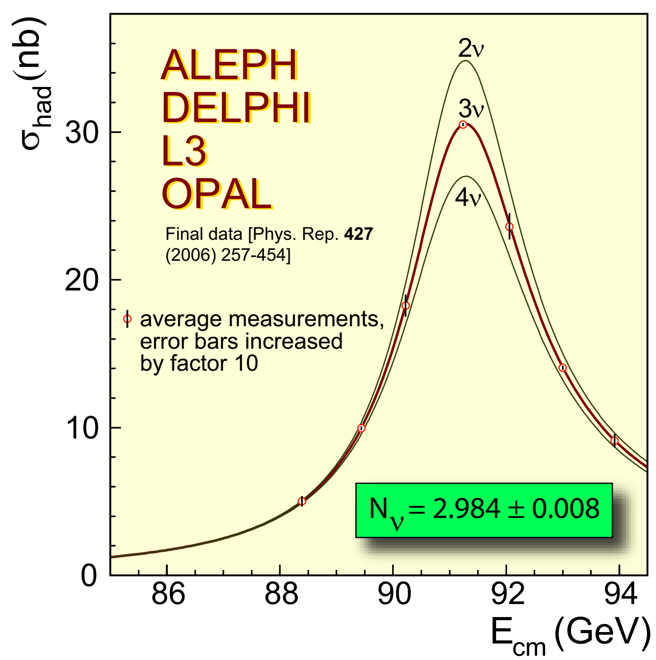
- Less minimal axion models have further possibilities ....

NEW PARTICLES

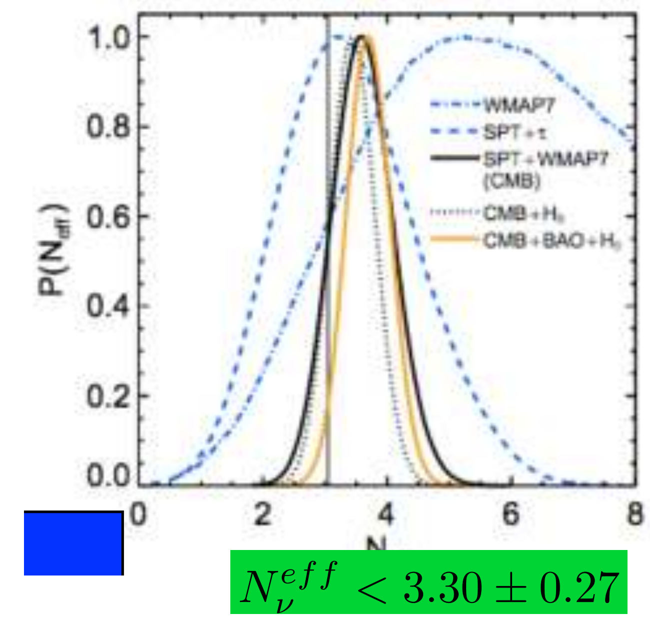
NEUTRINOS

- Number of Generations=3?
  - Why 3 copies?
- The necessary condition for the baryon asymmetry of the Universe - CP violation
- CP in the SM comes from the non-zero phase in the quark (and lepton) mixing matrices
- Non-zero phase appears only if the number of generations N ≥ 3

- The width of the Z-boson (LEP)



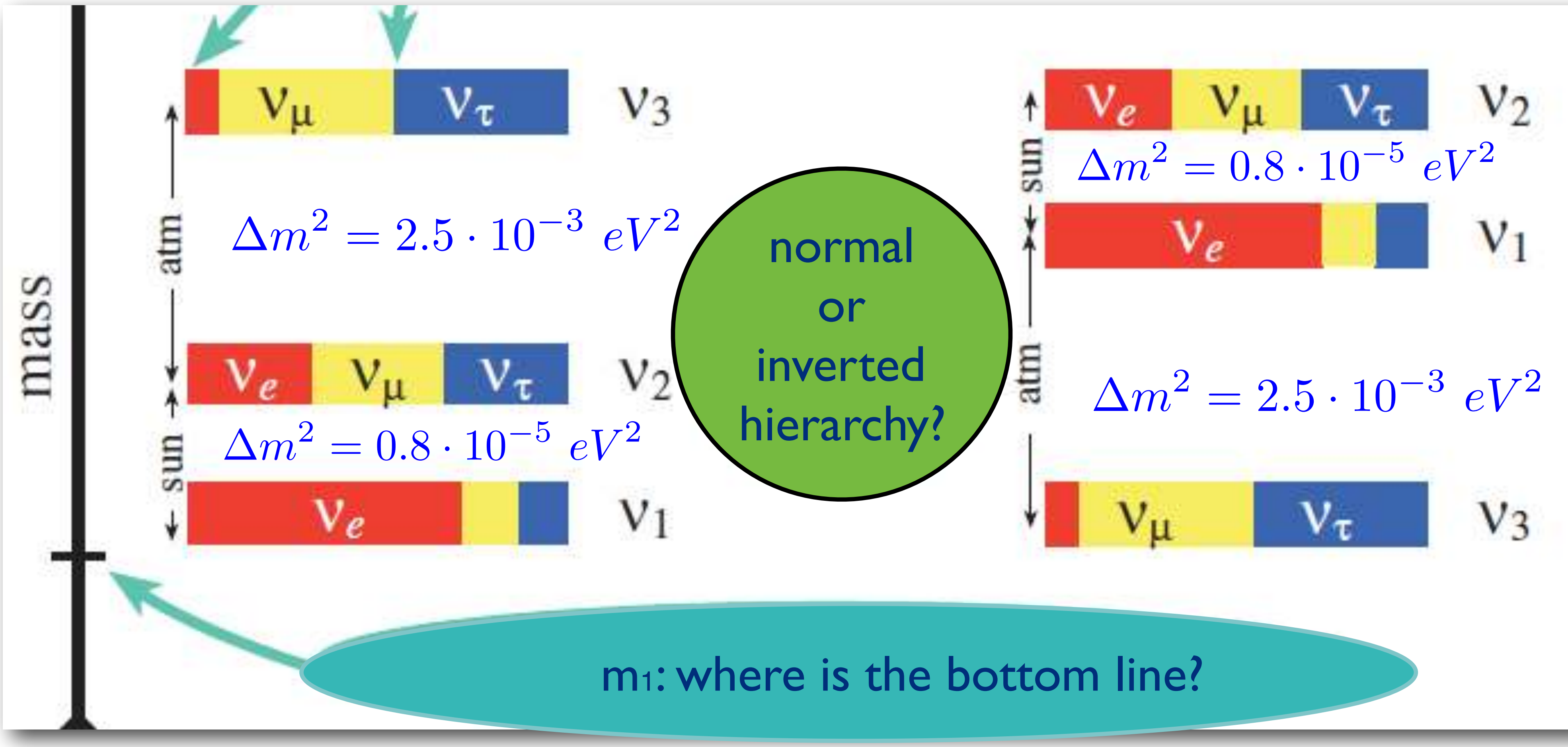
- The CMB spectrum (Planck)



- The fourth generation of quarks is excluded also by precision measurement of rare decays
- Do we see all neutrinos or there are heavy right-handed ones? (Majorana)
- Are there any new sterile neutrinos? (To release the constraints from LSND/MiniBoone and reactor anomaly, etc)

NEW PARTICLES NEUTRINOS

Neutrino masses



$m_{\nu_e} < 2\ eV$ → $m_{\nu_e} < 0.2\ eV$

$0.06\ eV < \sum m_\nu < 0.12\ eV$

β-decay

Troitsk-Mainz

KATRIN

Oscillations

CMB spectrum

Planck

DIRAC OR MAJORANA?

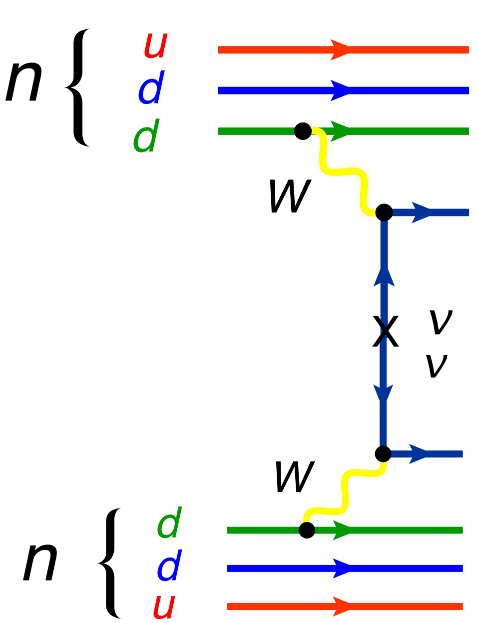
$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

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

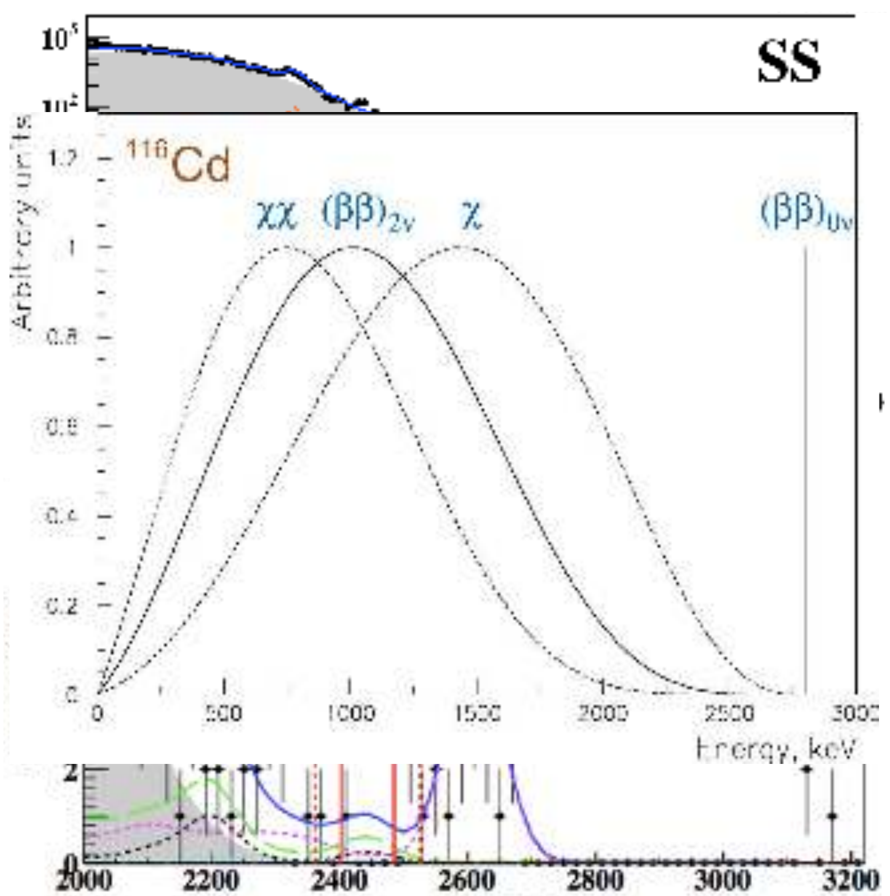
?

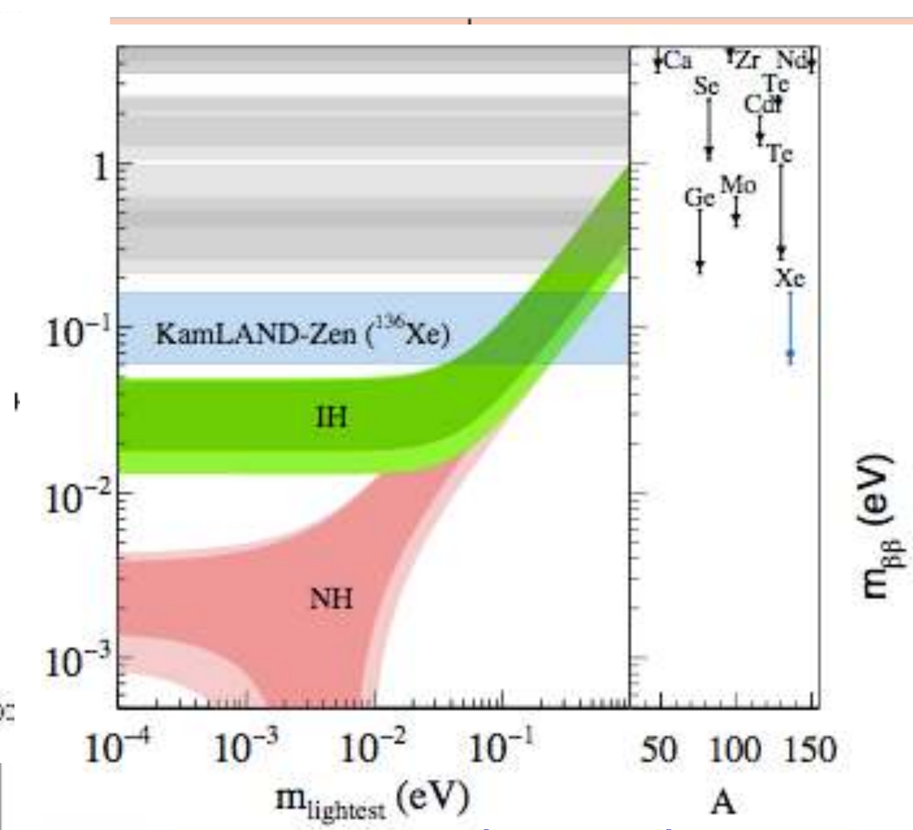
$$\nu_M = \nu_M^*$$
$$m_{\nu_{M_1}} \neq m_{\nu_{M_2}}$$

0νββ decay



Only Majorana





NEW PARTICLES

DARK MATTER

The Dark Matter is made of:

- Macro objects – Not seen
- New particles – right heavy neutrino

Not from the SM

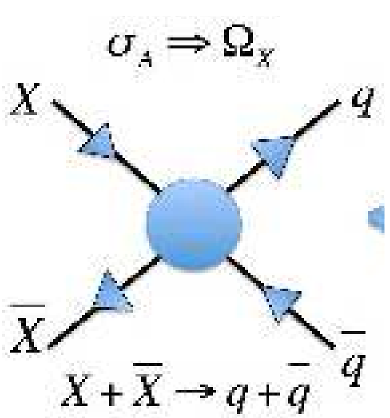
- axion (axino) — might be invisible (?)
- neutralino — mSUGRA — detectable in 3 spheres
- sneutrino — less theory favorable
- gravitino — might be undetectable (?)
- heavy photon — possible, but not related to the other models
- heavy pseudo-goldstone
- light sterile higgs

WIMP is our chance !

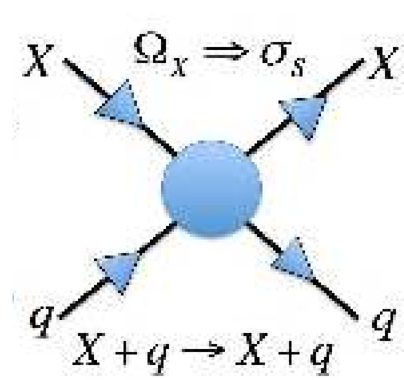
But we have to look elsewhere !

WIMP

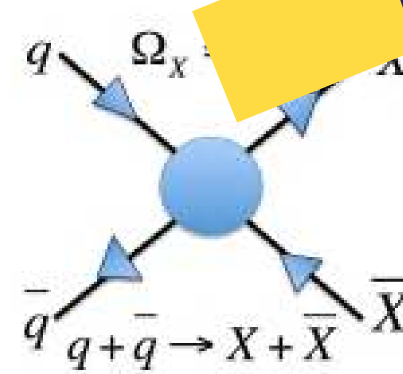
Annihilation in the halo



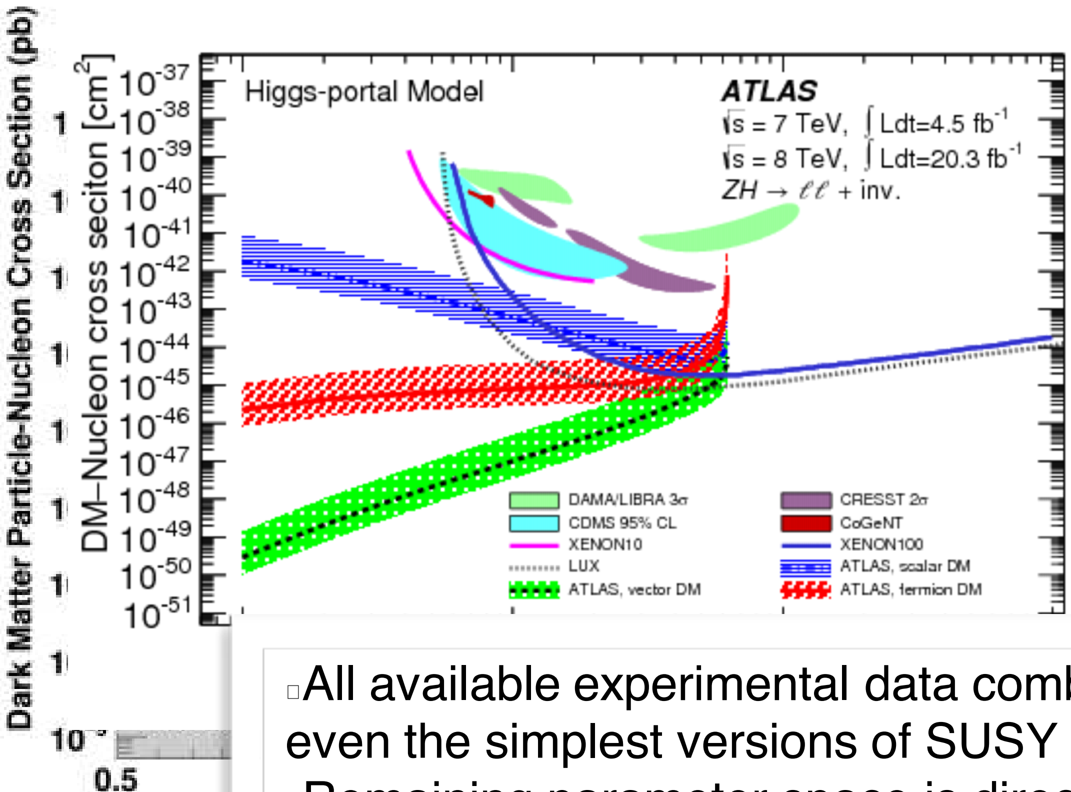
Scattering on a target

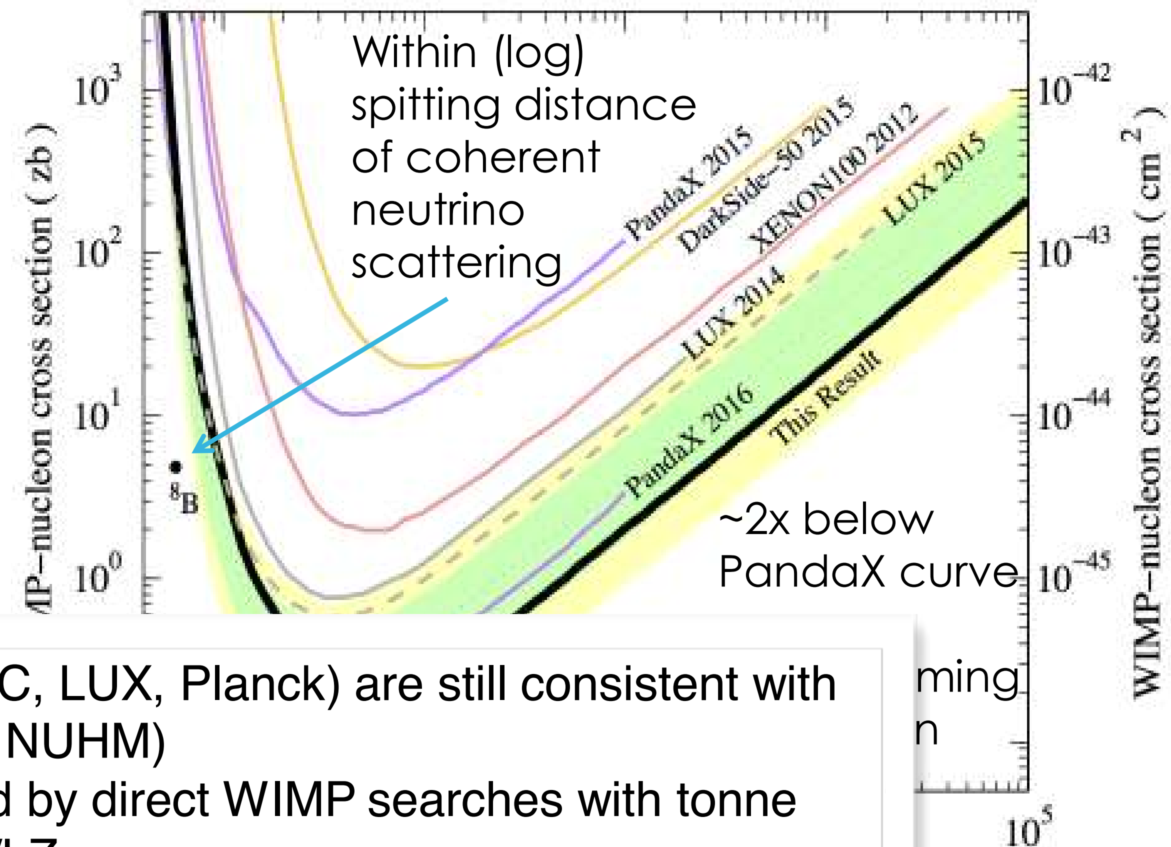


Creation at the LHC

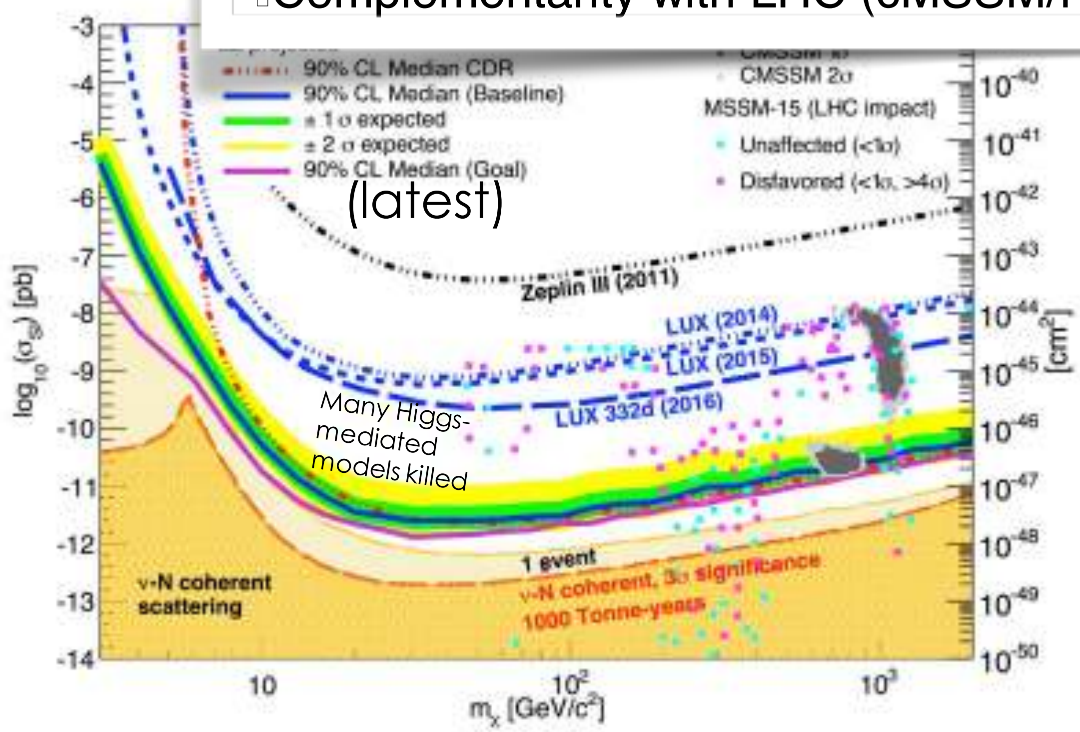


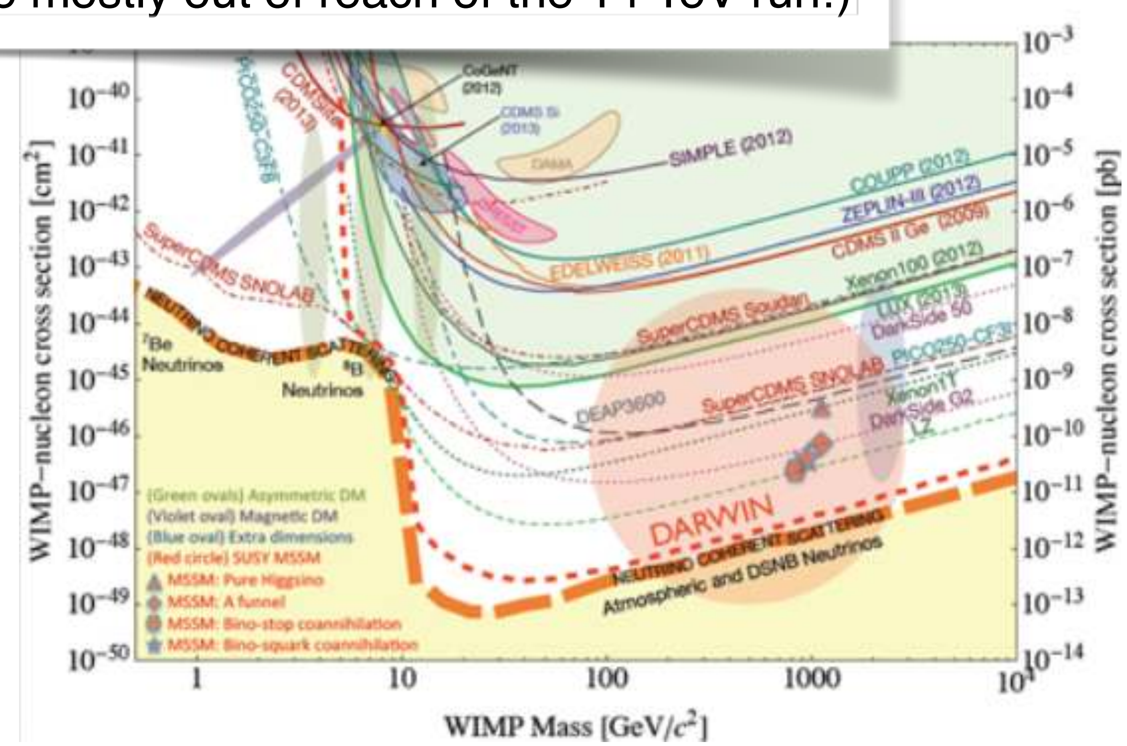
DARK MATTER: DIRECT DETECTION





- 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!)

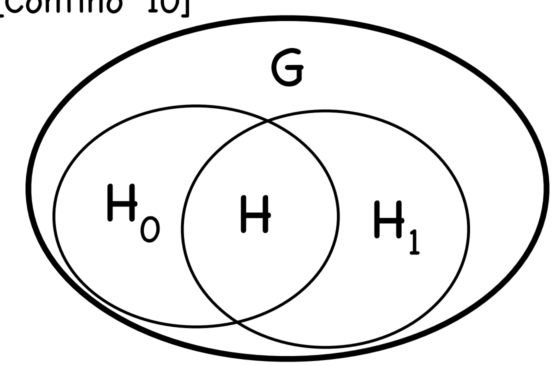




NEW FUNDAMENTAL OBJECTS

Higgs boson -> pseudo Numbu-Goldstone boson

[Contino '10]



Global symmetry G
broken to H of SM

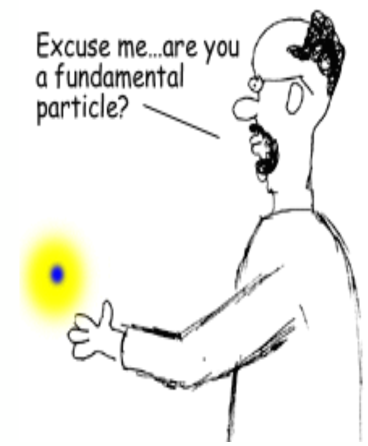
$$Higgs\ boson \Leftrightarrow \pi - meson$$
$$W, Z\ bosons \Leftrightarrow \rho - mesons$$

Should be

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

Advantage: No artificial scalar field
Protection from high energy physics

COMPOSITENESS



Quarks and Leptons made of preons

New strong confining forces

Technicolor
Walking Technicolor
Extended Technicolor
...

- No new excited states observed
- Problems with precision EW observables
- No viable simple scheme

Still possible

NEW DIMENSIONS

EXTRA SPACE DIM

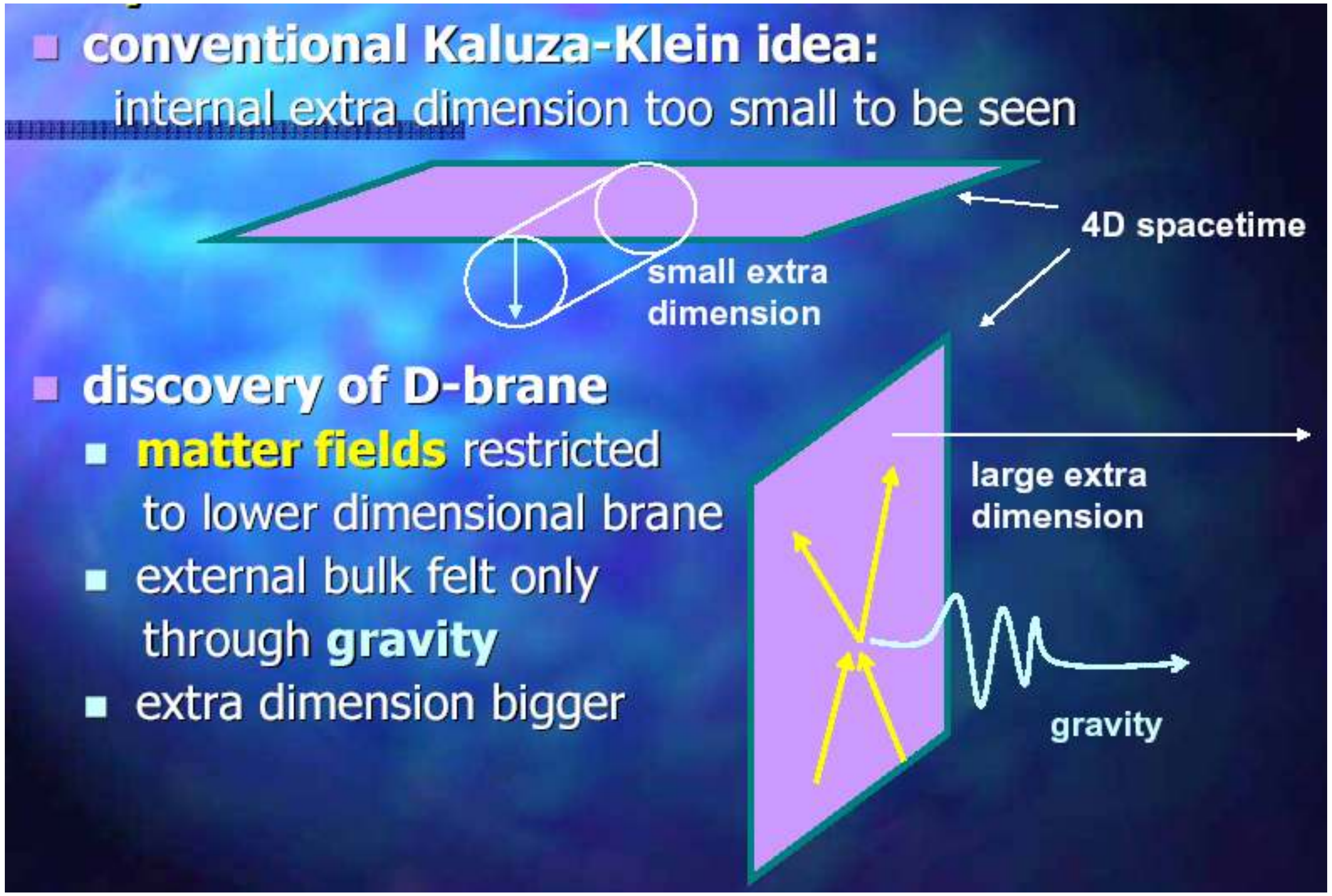
$$1+3 \to 1+n, \; n>3$$

Motivations

1. String theory
2. Interesting possibility that opens wide opportunities

- String theory suffers conformal anomalies that make it inconsistent.
- Conformal anomaly cancels at D=26 for a bosonic string and D=10 for a fermionic string

Why don't we see extra dimensions



PHENOMENOLOGY OF EXTRA D

Accelerator signatures

- Gravitational radiation in the bulk => missing energy

Present LHC bounds $M_* \geq 3-5$TeV

- Massive string vibrations => resonances in dijet distribution

$$M_j^2 = M_0^2 + M_s^2 j$$

- Higher spin excitations gluons with stron

present LHC li

- Large T reso ns

$$M_k = \quad 1, 2, \ldots$$

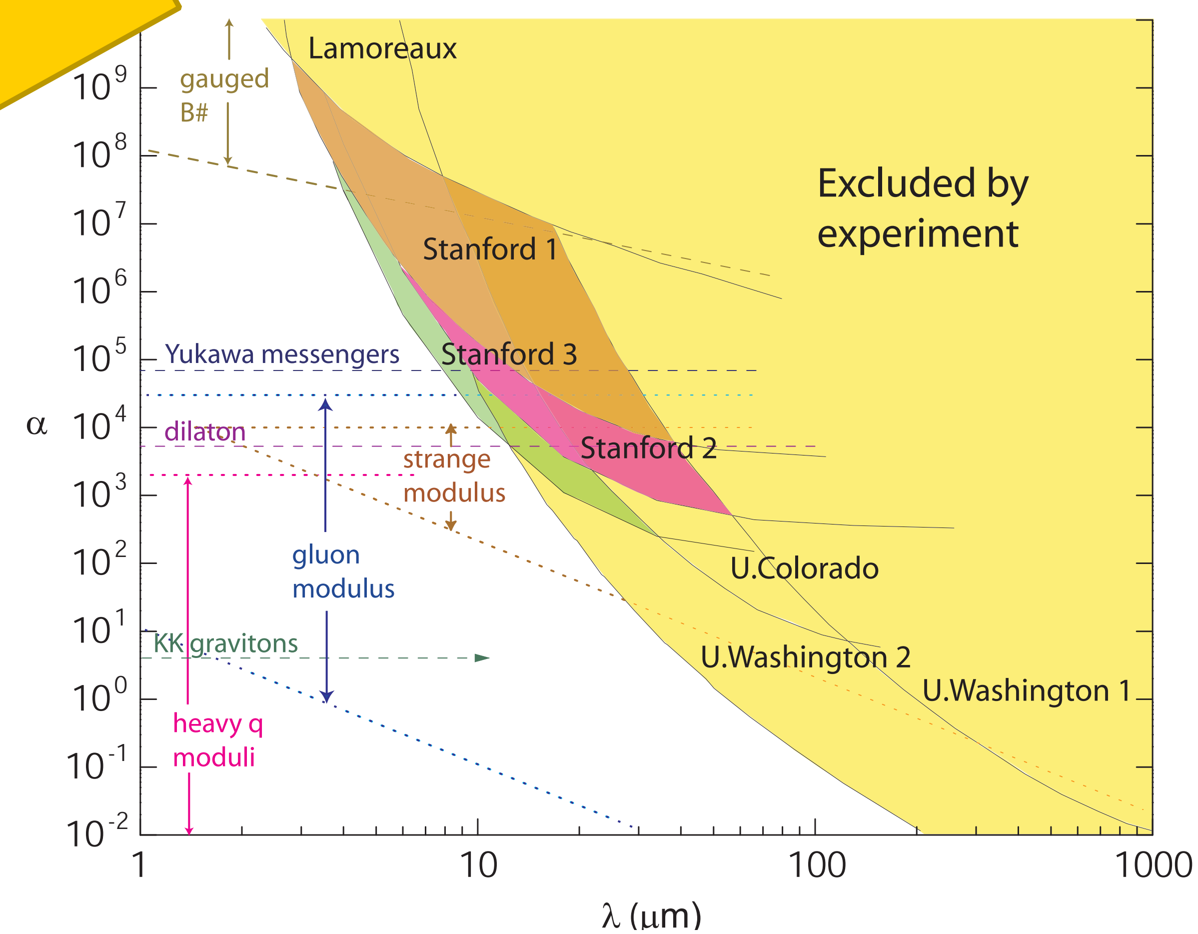
experime

$$R^{-1} \geq \quad - 4 \quad \text{TeV}$$

Vast phenomenology but no indication so far

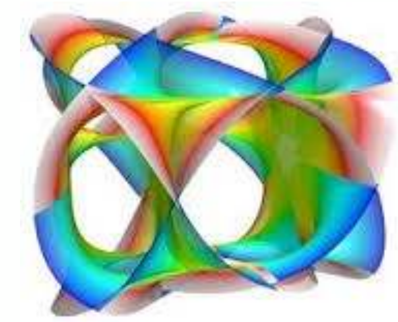
- change of Newton's law at short distances (detectable only in case of 2 large extra dim)
- ew short range forces (light scalars and uge fields)

$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

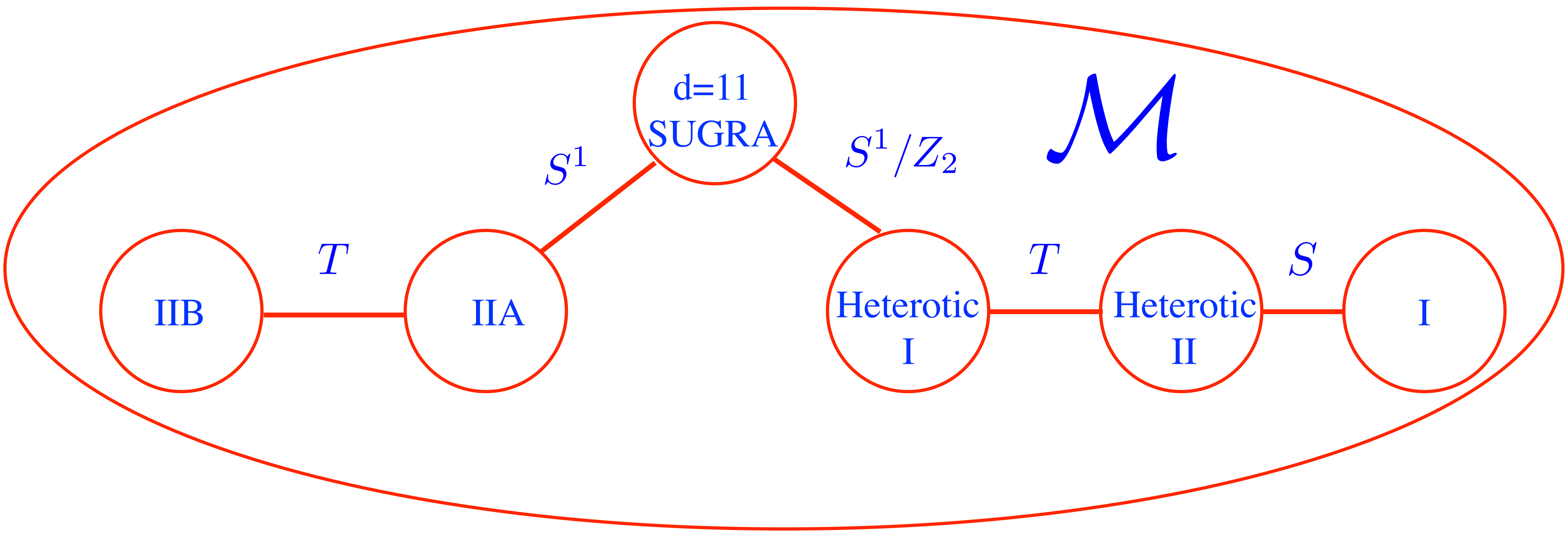


NEW PARADIGM

STRING THEORY



- ✳ There are five types of string theories (IIA, IIB, I, two Heterotic)
- ✳ All five string theories are only consistent in 10 space-time dimensions
- ✳ All five string theories have world-sheet supersymmetry and lead to space-time-supersymmetry in 10 dimensions
- ✳ All five string theories are related and part of a single ''theory'': M-theory



M-theory is a patchwork of the constituent theories plus many "rules".

CONCLUDING REMARKS

- LHC experiments are at the front line of mystery land: be patient and ready for unexpected
- Target #1: Higgs sector
- Target #2: Dark Matter
- Target #3: Neutrino sector
- Target #4: New physics (supersymmetry)
- Future development of HEP crucially depends on LHC outcome
- Complimentary searches for dark matter and insights in neutrino physics are of extreme importance
- The areas that were left behind come to the front: confinement, exotic hadrons, dense hadron matter