Landscape view at the edge of Mystery

Dmitry Kazakov

JINR (Dubna) ITEP (Moscow) MIPT (Dolgoprudny)

The Standard Theory

- Three gauged symmetries SU(3)xSU(2)xU(1)
- Three families of quarks and leptons (3x2, 3x1, 1x2, 1x1)
- 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

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?
- Are there any indications for physics beyond the SM?
- Is there another scale except for EW and Planck?
- Is it compatible with Cosmology?

Why's?

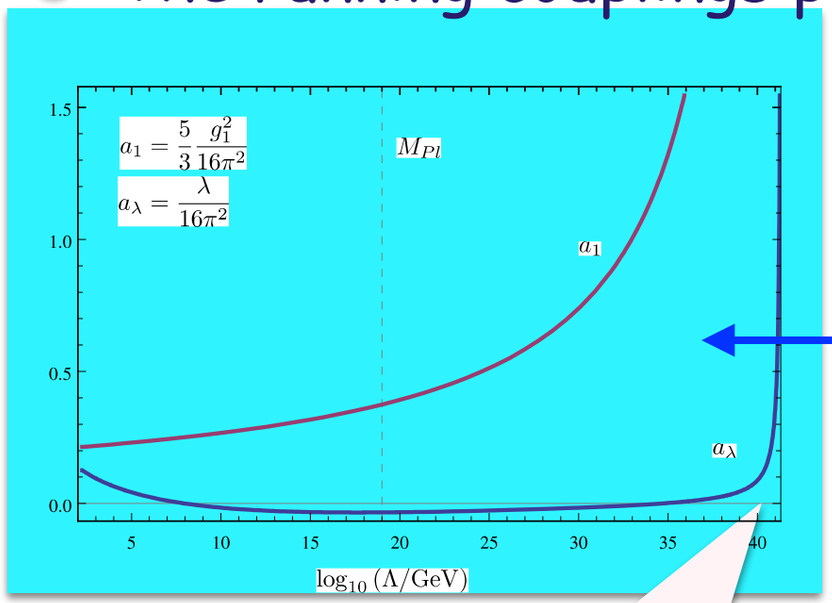
- why the SU(3)xSU(2)xU(1) ?
- why 3 generations ?
- why quark-lepton symmetry?
- why V-A weak interaction?
- why L-R asymmetry?
- why B & L conservation?
- etc

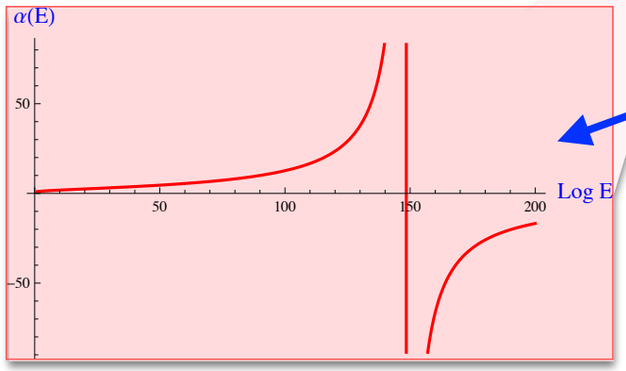
How's?

- how confinement actually works ?
- how the quark-hadron phase transition happens?
- how neutrinos get a mass?
- 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





- The ghost pole exist for the U(1) coupling and for the Higgs coupling, but … beyond the Planck scale

- The Landau pole has a wrong sign residue that indicates the presence of unphysical ghost fields - intrinsic problem and inconsistency of a theory

This is the ghost pole

$$\alpha_1(Q^2) = \frac{\alpha_{10}}{1 - \frac{41}{10}\frac{\alpha_{10}}{4\pi}\log(Q^2/M_z^2)}$$

$$Q^* = M_Z e^{\frac{20\pi}{41\alpha_{10}}} \sim 10^{41}\ GeV$$

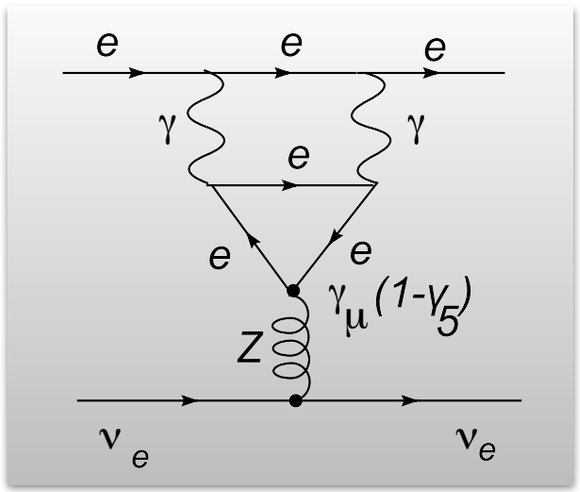
- The situation may change in GUTs due to new heavy fields @ the GUT scale

- requires modification of the ST at VERY high energies

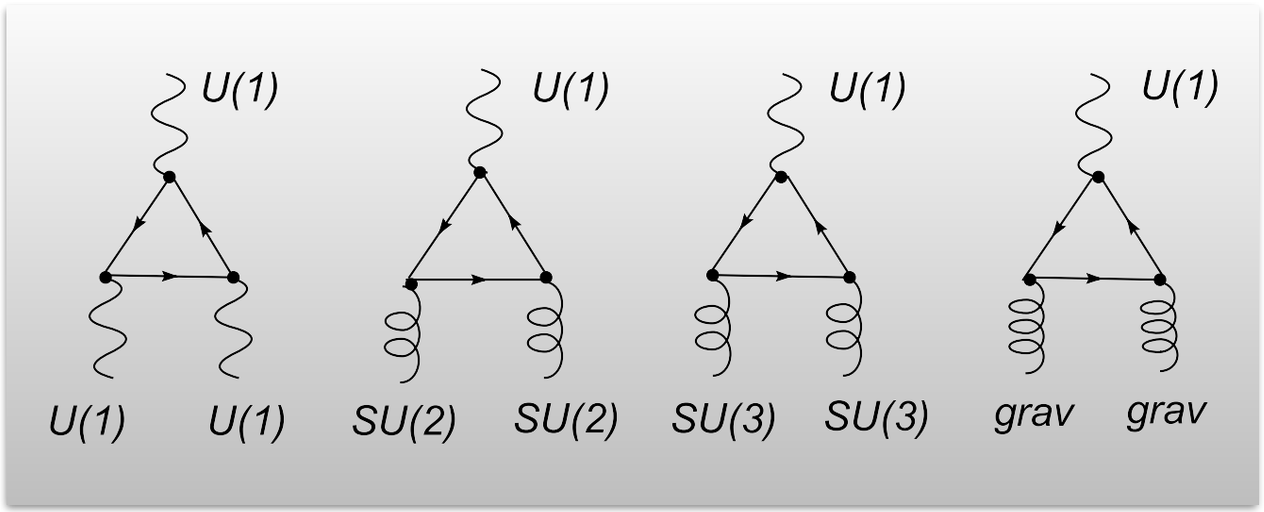
Is the SM consistent quantum field theory?

- Quantum anomalies may ruin the ST if not cancelled among quarks and leptons

This is the anomalous diagram



Anomalies in the SM



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

$$\uparrow \quad \uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow$$

$$colour \quad u_L \qquad d_L \qquad u_R \qquad d_R \qquad \nu_L \qquad e_L \qquad e_R.$$

$$TrY_L = 3\left(\frac{1}{3} + \frac{1}{3}\right) - 1 - 1 = 0,$$

$$TrY_q = 3\left(\frac{1}{3} + \frac{1}{3} - \frac{4}{3} - (-\frac{2}{3})\right) = 0,$$

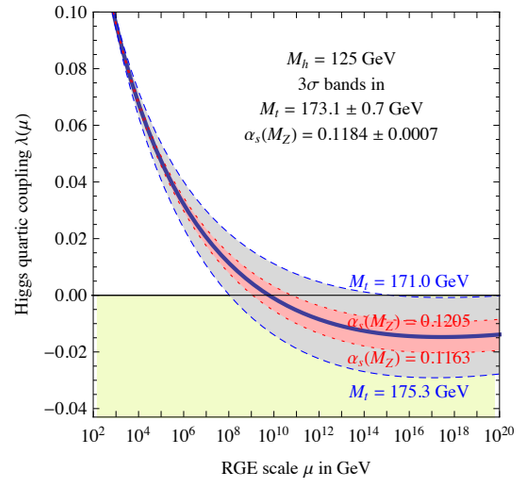
$$TrY = 3\left(\frac{1}{3} + \frac{1}{3} - \frac{4}{3} - (-\frac{2}{3})\right) - 1 - 1 - (-2) = 0.$$

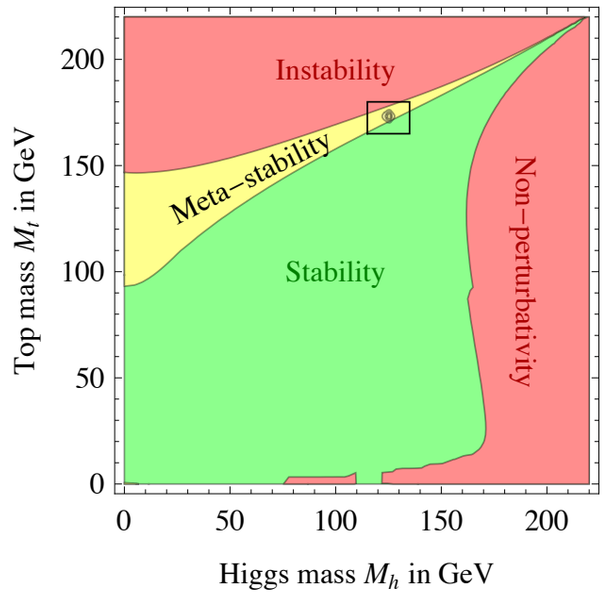
- cancellation of anomalies requires quark-lepton symmetry
- this is a hint towards the Grand Unified Theories

Is the SM consistent quantum field theory?

- Quantum corrections can make the vacuum unstable

- the whole construction of the SM may be in trouble being metastable or even unstable
- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and accuracy





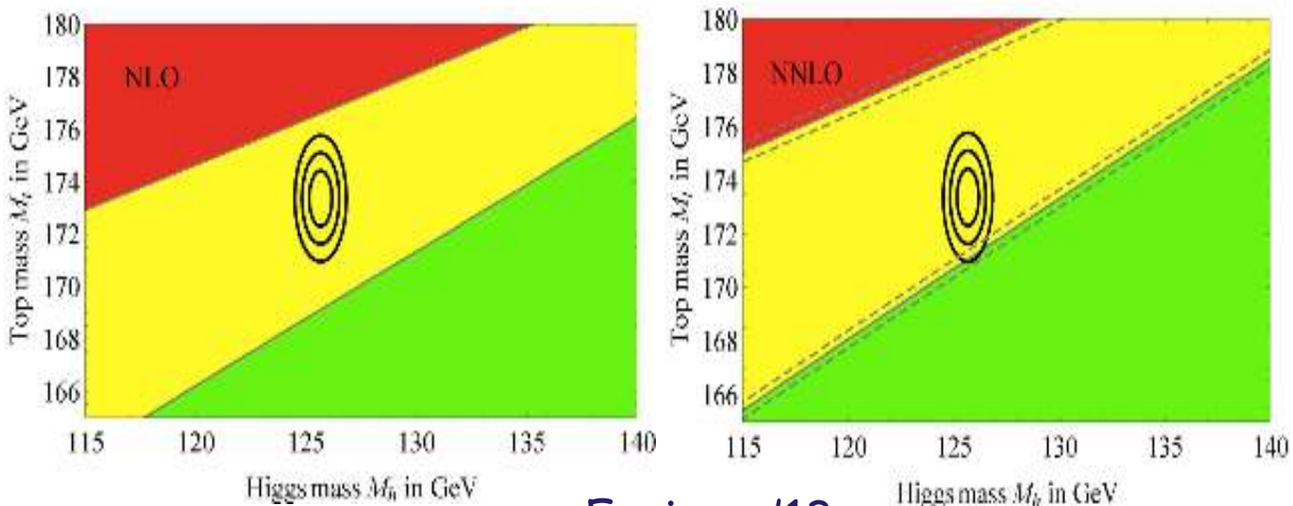
The way out might be the new physics at higher scale:

- 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

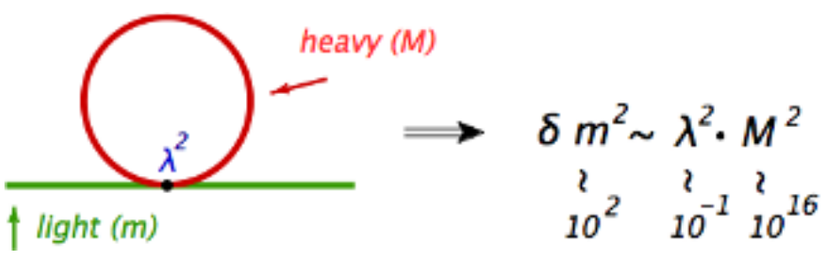


Espinosa'13

Is the SM consistent quantum field theory?

- New physics at high scale may destroy the EW scale of the ST

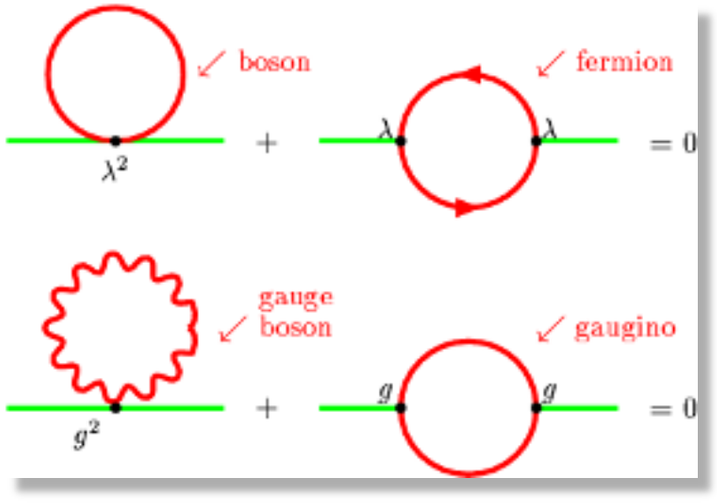
Quantum corrections to the Higgs potential due to New physics



- The Higgs sector is not protected by any symmetry
- creates the hierarchy problem $\frac{m_H}{m_{GUT}} \sim 10^{-14}$
- requires modification of the ST

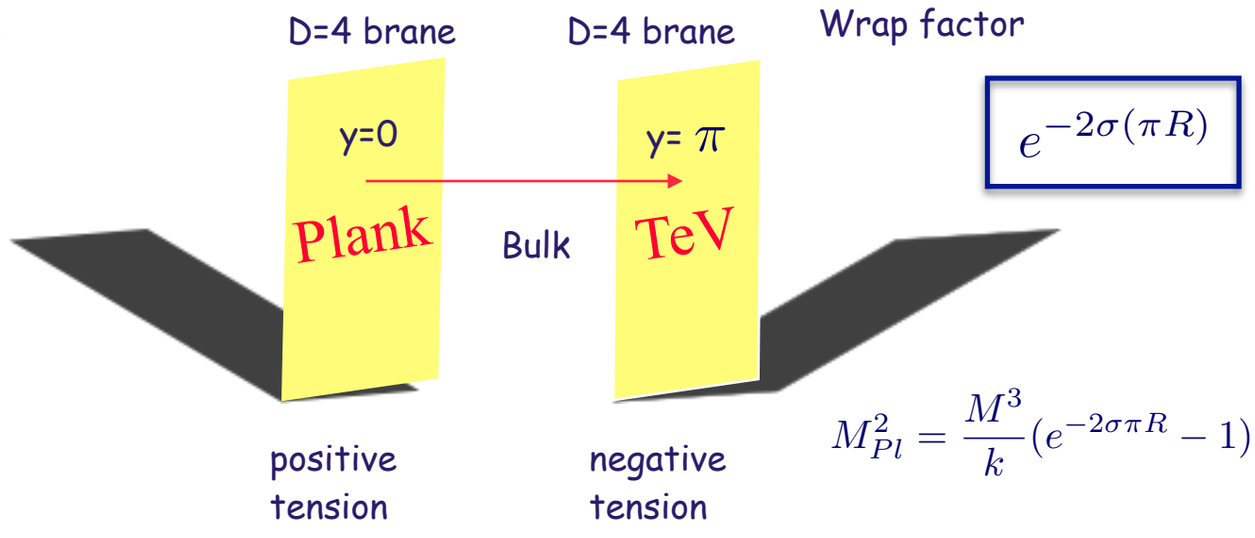
- the way out might be the new physics at higher scale:

SUSY is one example:



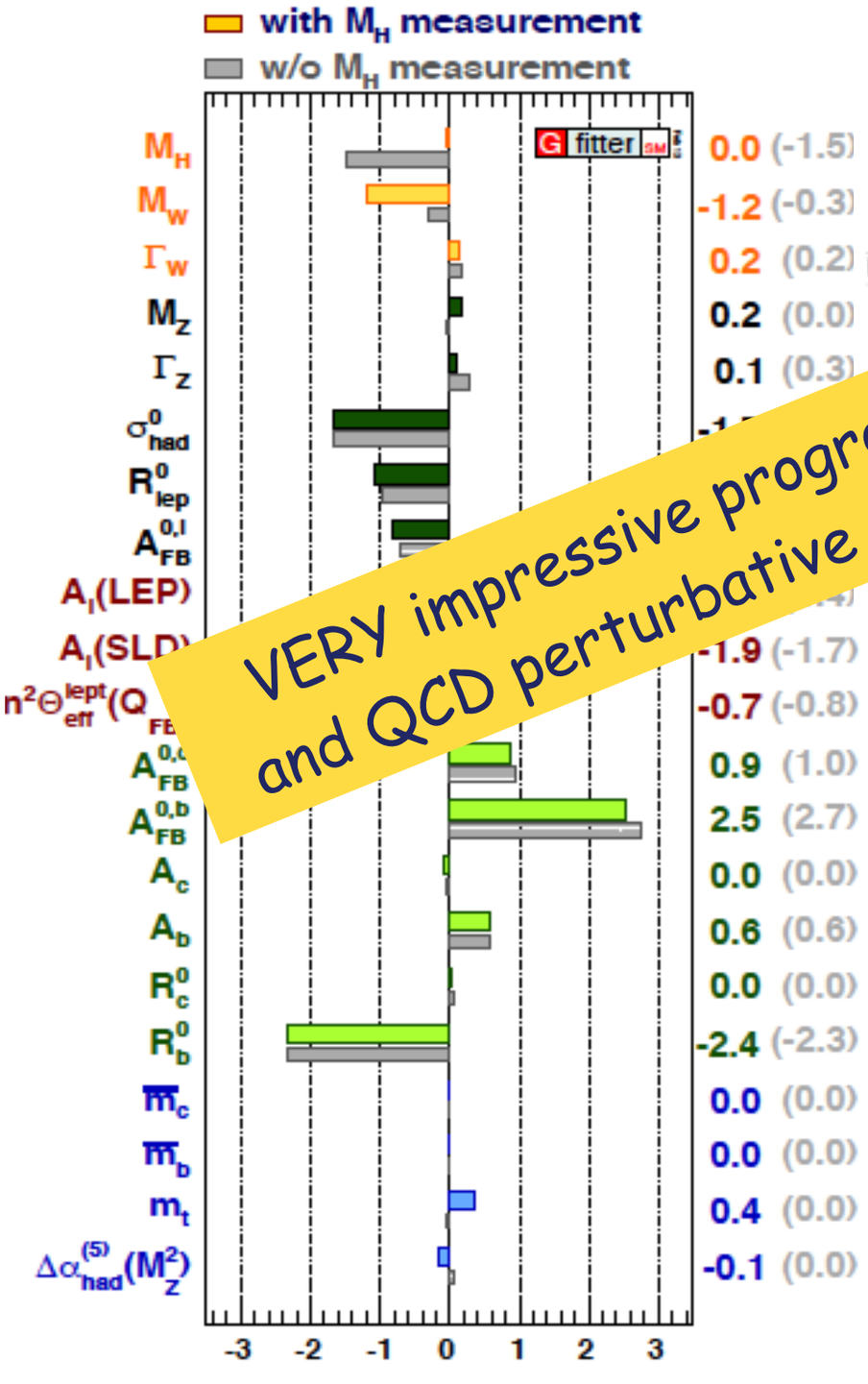
- cancellation with superpartners up to $\Delta m^2 \sim 1\ TeV$
- little hierarchy problem $m_{SUSY} \geq TeV$

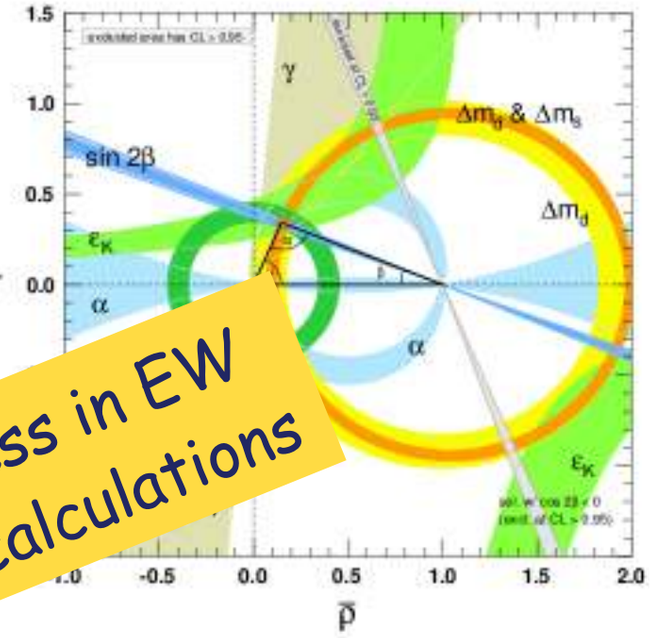
Extra dimensions is another example:

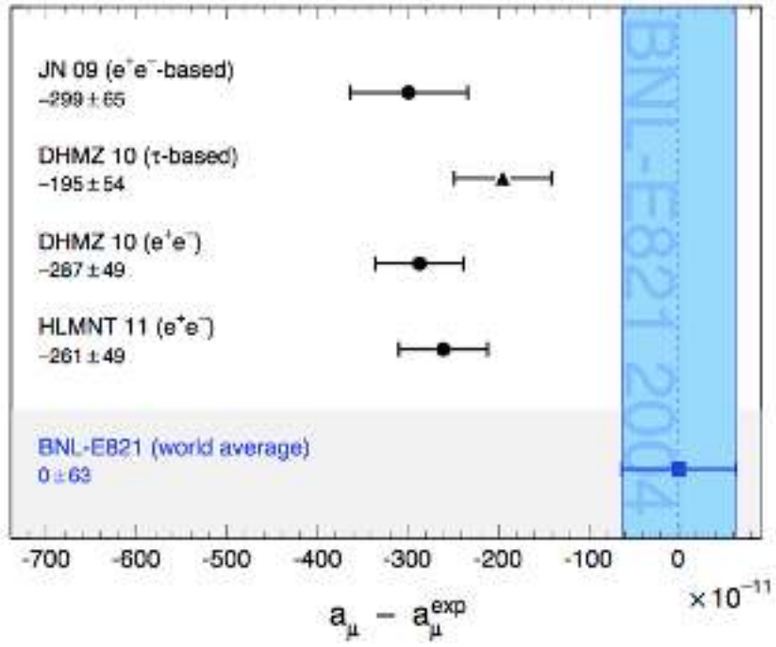


Does the ST describes all experimental data?

- EW observables pool







- Flavour Physics observ

VERY impressive progress in EW and QCD perturbative calculations

- Forward-backward asymmetries in LEP data - ignored problem
- g-2 of muon - the main pain in the neck -3 σ gap
- Vub inclusive-exclusive discrepancy

- 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

Physics with a single generation

Back to the middle of the XX century





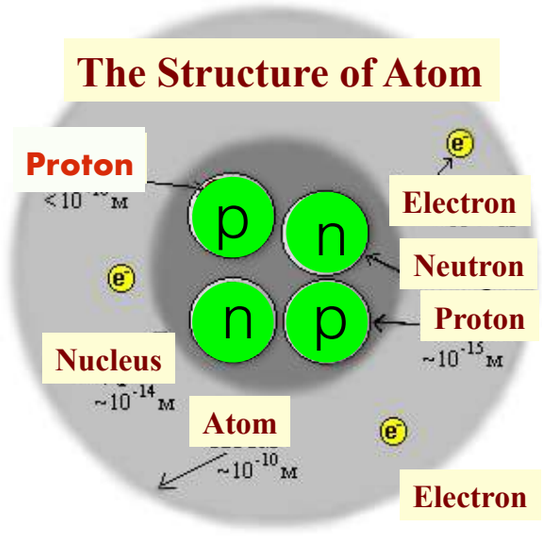
All the world around us is made of the 1st generation

p 1919 | c 1974 | t 1995 | ν_e 1956 | ν_μ 1963 | ν_τ 2000

n 1932 | s 1947 | b 1977 | e 1897 | μ 1936 | τ 1975

γ | W,Z 1983 | H 2012 | G

- Muon - heavy electron - 2nd generation ?
- K-meson - strangeness ?
- Quark model (OK again?)
- GIM Mechanism, J/Psi - charm -2nd generation
- CP-violation: where it comes from?

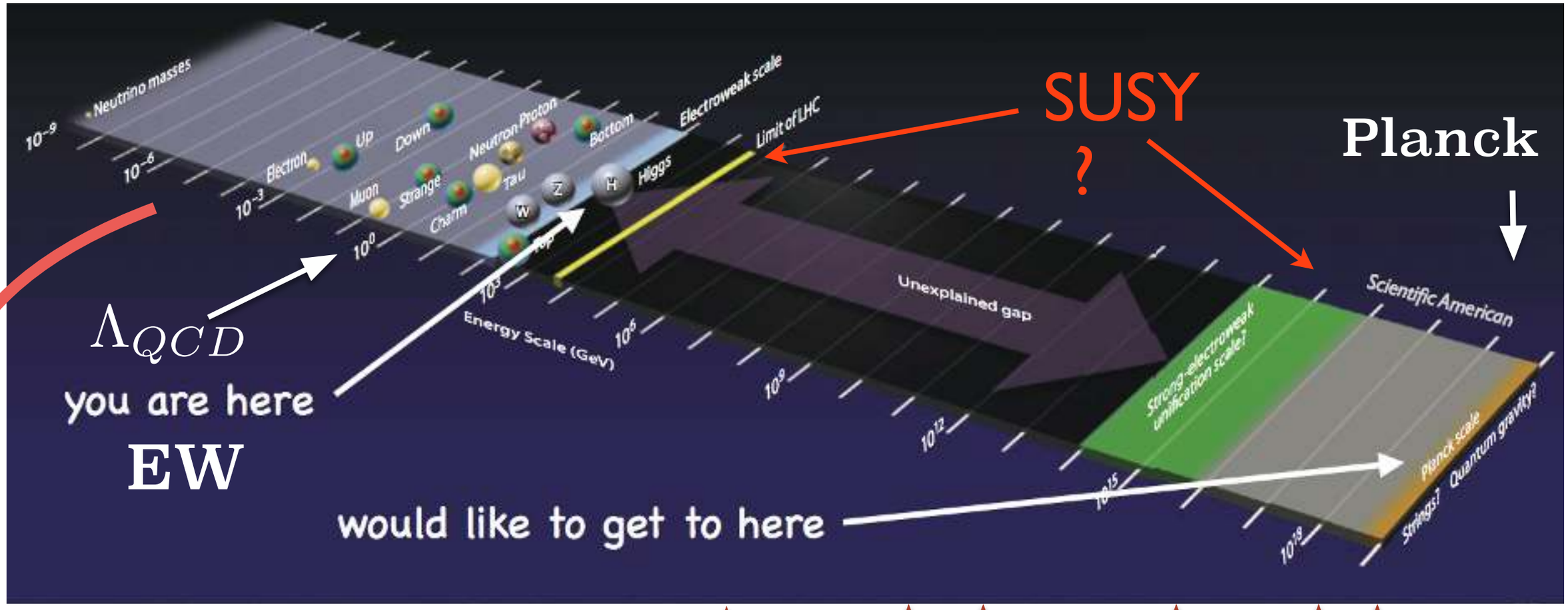


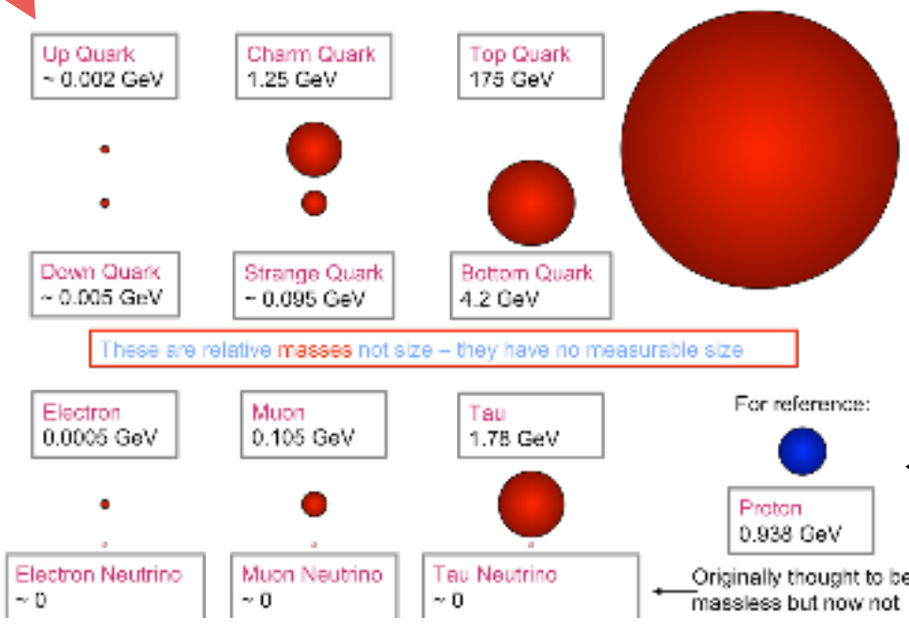
- Who expected new physics to come?
- What scale of NP?

<u>Astrophysics & Cosmology challenge</u>

- Baryon asymmetry of the Universe
- Description of the Dark Matter

Is there another scale except for EW and Planck?





?

Vacuum Stab ~ 10^{11}GeV

Majorana scale ~ 10^{12} GeV

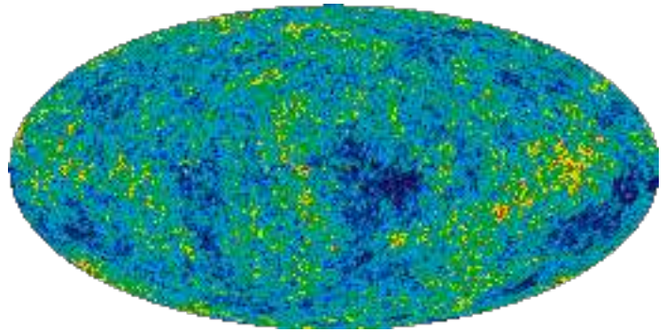
GUT scale ~ 10^{16}GeV

String scale ~ 10^{18} GeV

Planck scale ~ 10^{19}GeV

?

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

- Relic abundance of the Dark Matter

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

- Understanding is beyond the SM

- Number of neutrinos

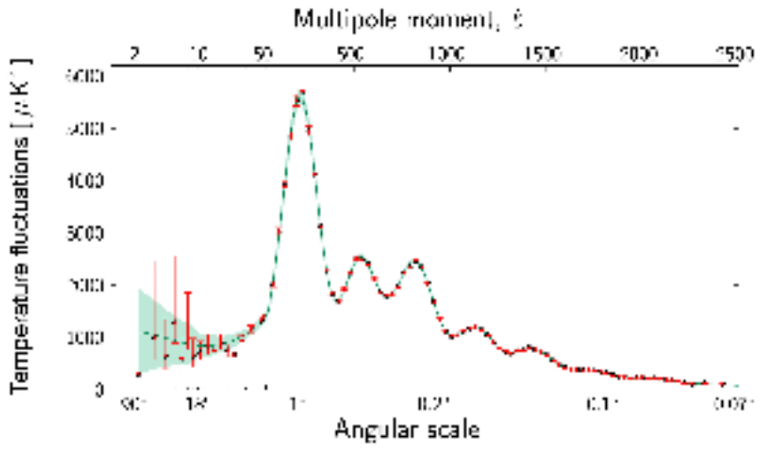
$$N_{eff} = 3.52 \pm 0.47 \quad 95\%\ CL$$
$$Planck + WP + highL + BAO + HST$$

- Well suits the SM
  q <-> l

- Masses of neutrinos

$$\Sigma m_\nu\ [eV] < 1.11(0.22)$$
$$Planck + WP + lensing + HST$$

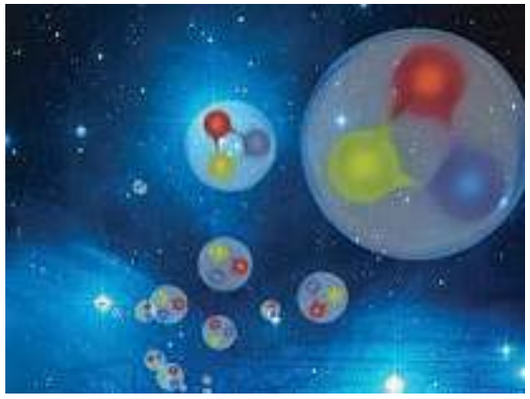
- Probably a hint towards new physics



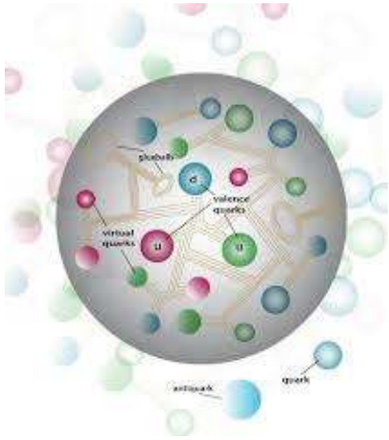
Do we understand confinement?

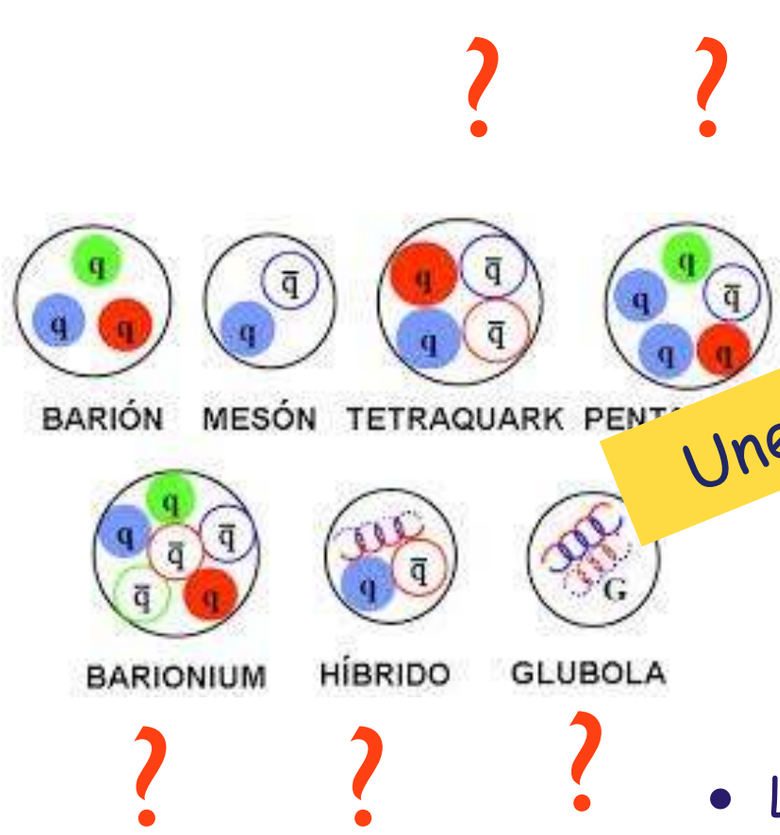
Challenging problem in particle physics well inside the SM

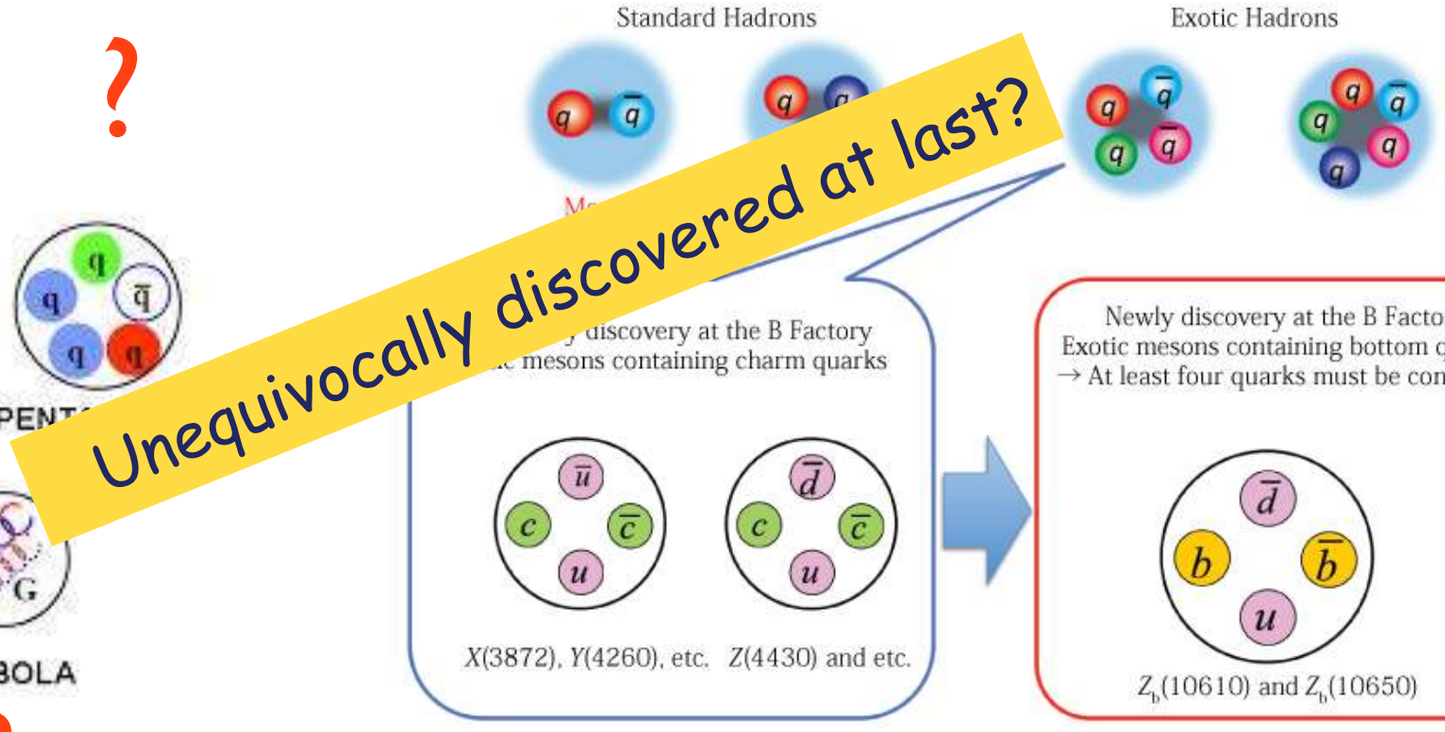
Time to come back?



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

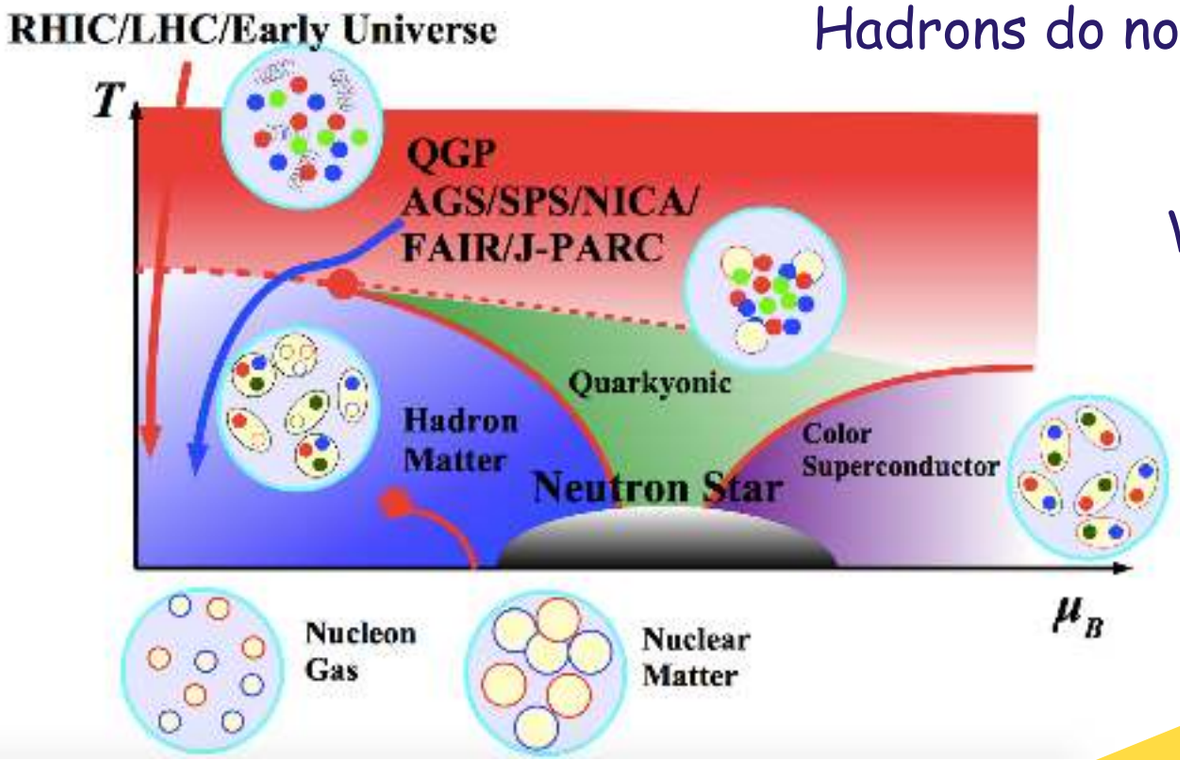




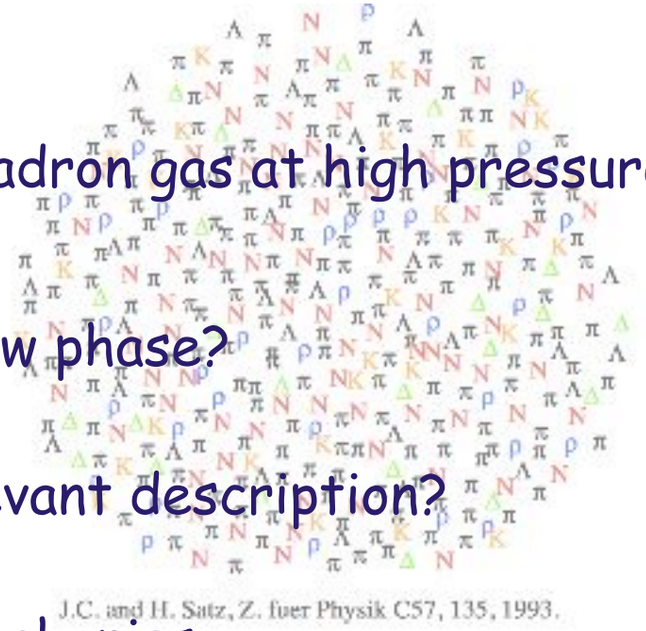


- Lattice gauge theories
- Holographic approach
- Gauge theories in dual description
- Back to analyticity & unitarity ?

Dense hadron matter - new phase?



Hadrons do not exist above the Hagedorn temperature



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

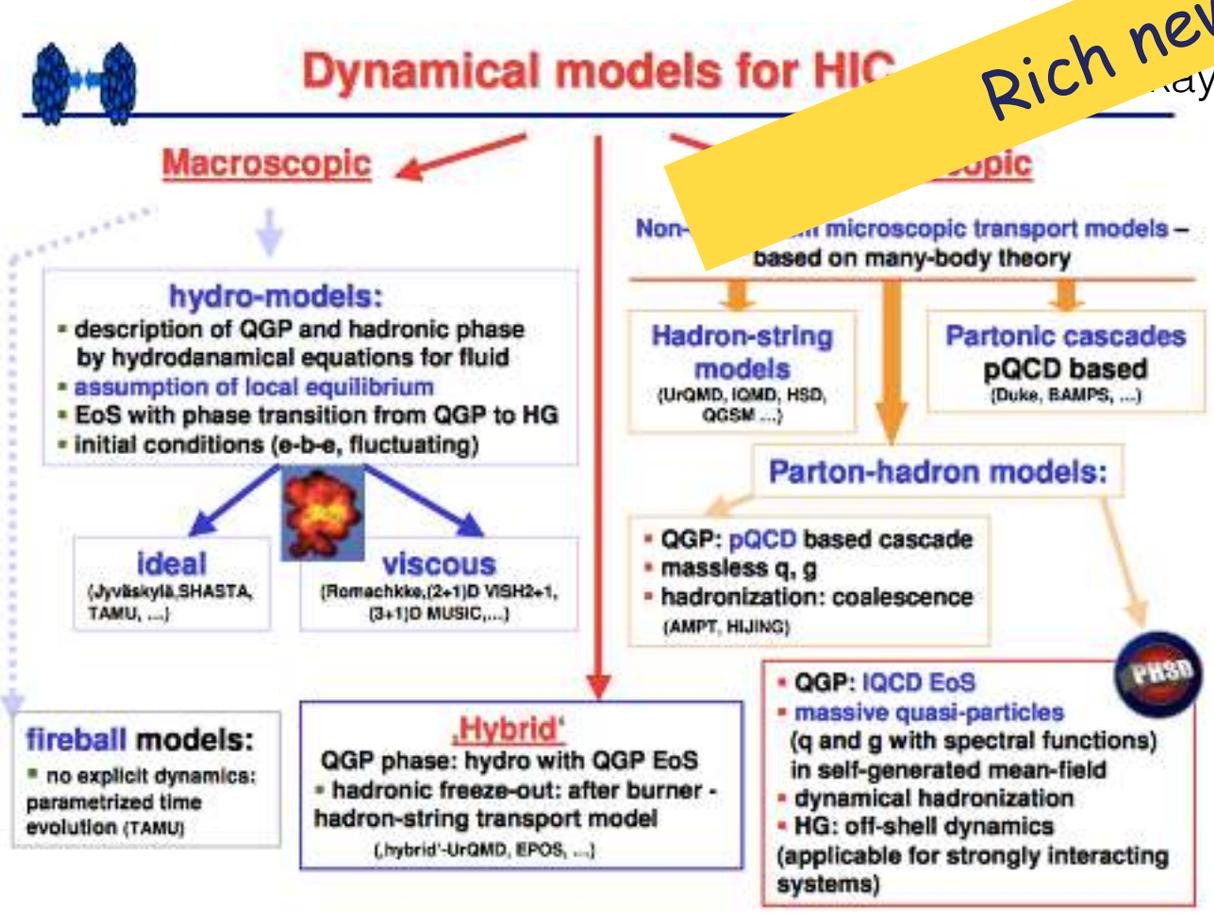
What happens with hadron gas at high pressure?

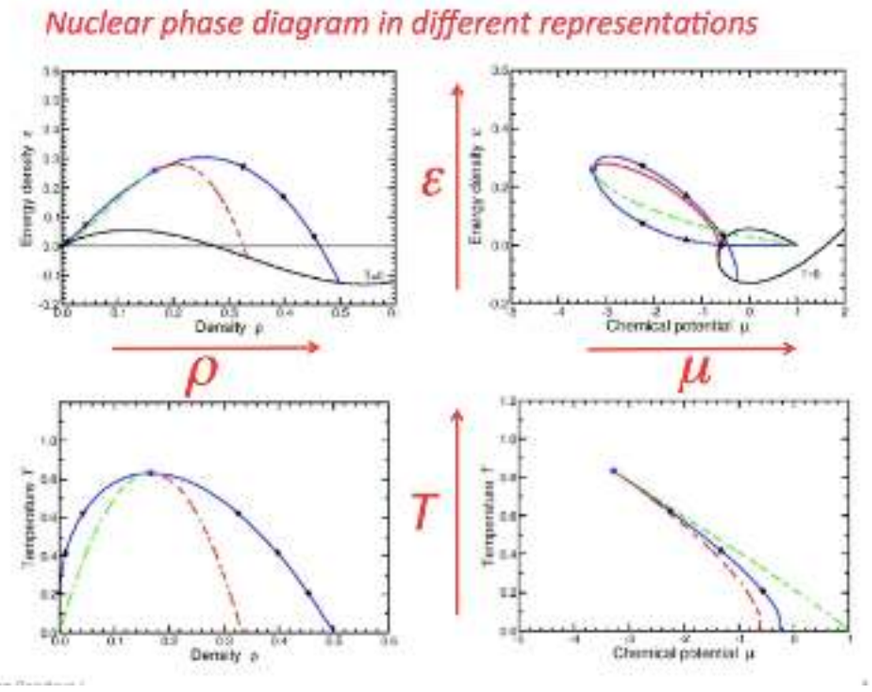
How to get the new phase?

What is the relevant description?

Rich new phenomena

statistical mechanics,
nonequilibrium thermodynamics
hydrodynamics,
dual models - holography





Search for New Physics

The Higgs Boson - Target # 1

Is it the SM Higgs boson or not?

What are the alternatives?

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

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

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

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

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

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

M.Spannowsky

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

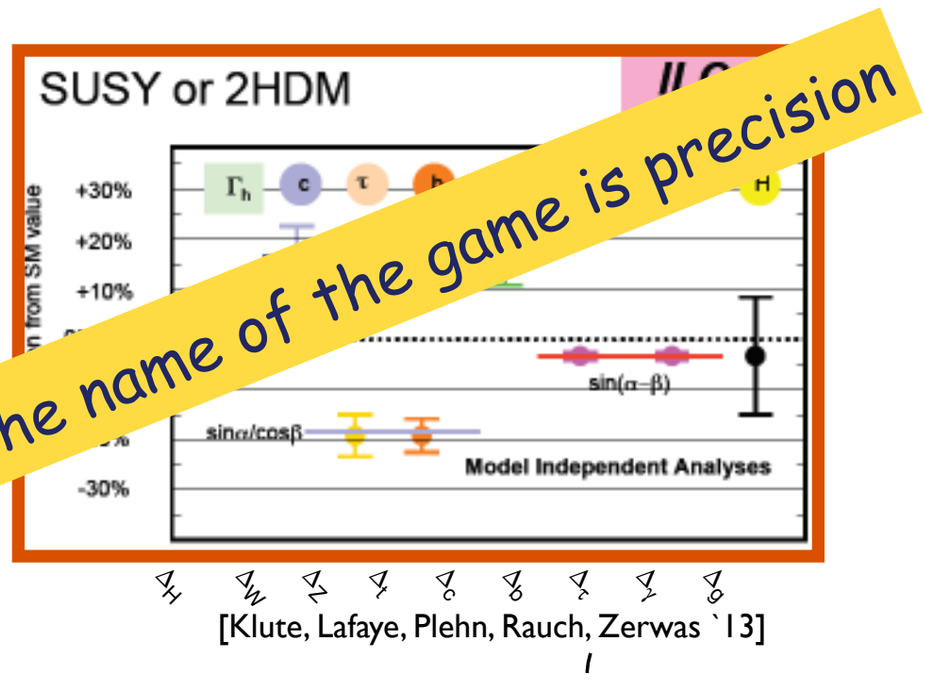
Search for New Physics

The Higgs Boson - Target # 1

Is it the SM Higgs boson or not?

How to probe?

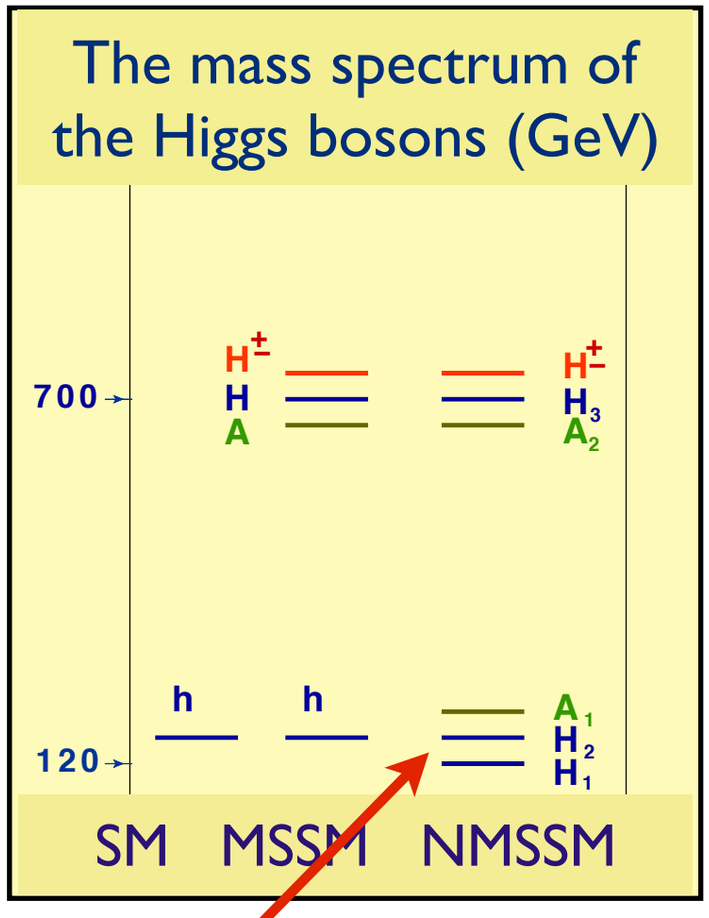
- Probe deviations from the SM Higgs couplings



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

- Perform direct search for additional scalars



We may have found one of these states

Search for New Physics

The Dark Matter - Target # 2

The Dark Matter is made of:

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

Not from the SM

- axion (axino)
- neutralino
- sneutrino
- gravitino
- heavy photon
- heavy pseu… one
- light sterile …iggs

mSUGRA

not favorable but possible

might be invisible (?)

detectable in 3

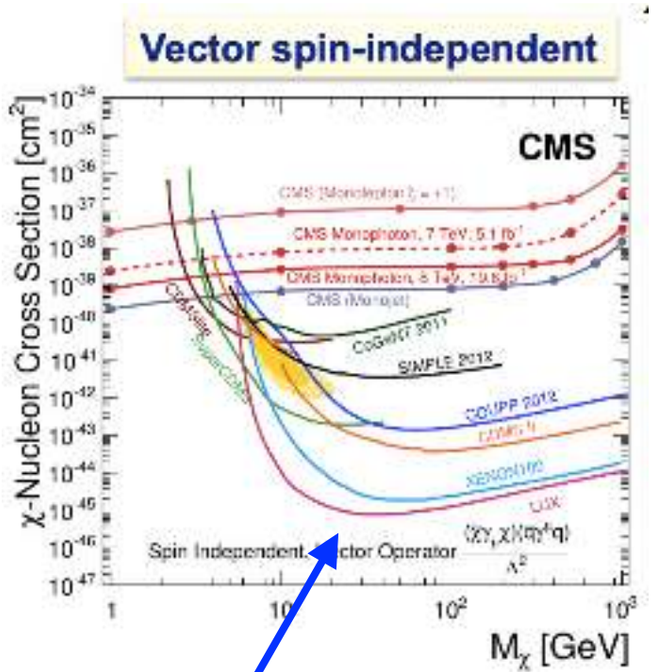
less the…

pos… und…

…o the other …odels

WIMP is our chance !

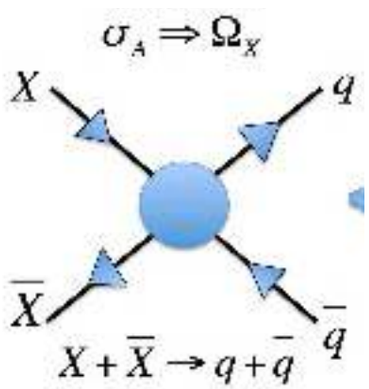
But we have to look elsewhere !



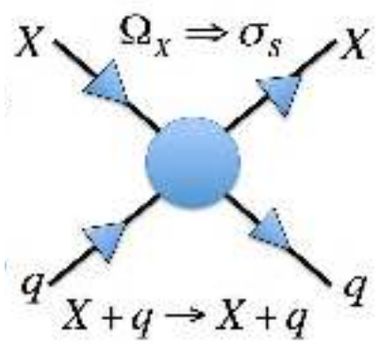
- Already close to neutrino floor
- Still have a chance

WIMP

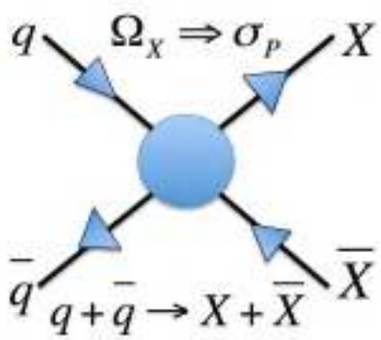
Annihilation in the halo



Scattering on a target



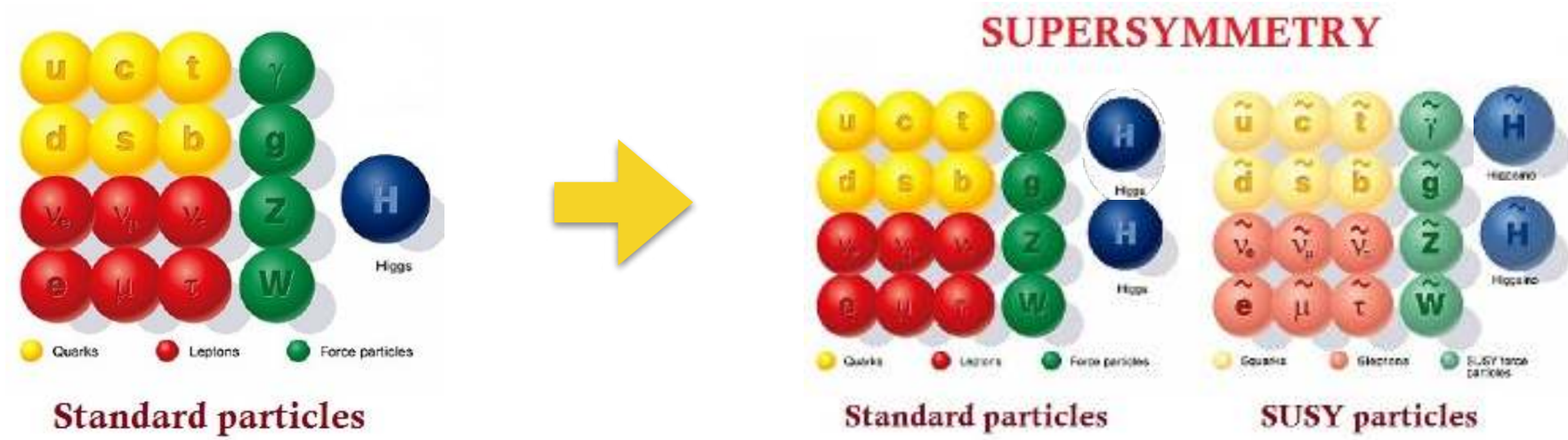
Creation at the LHC



Search for New Physics

Supersymmetry - Target # 3

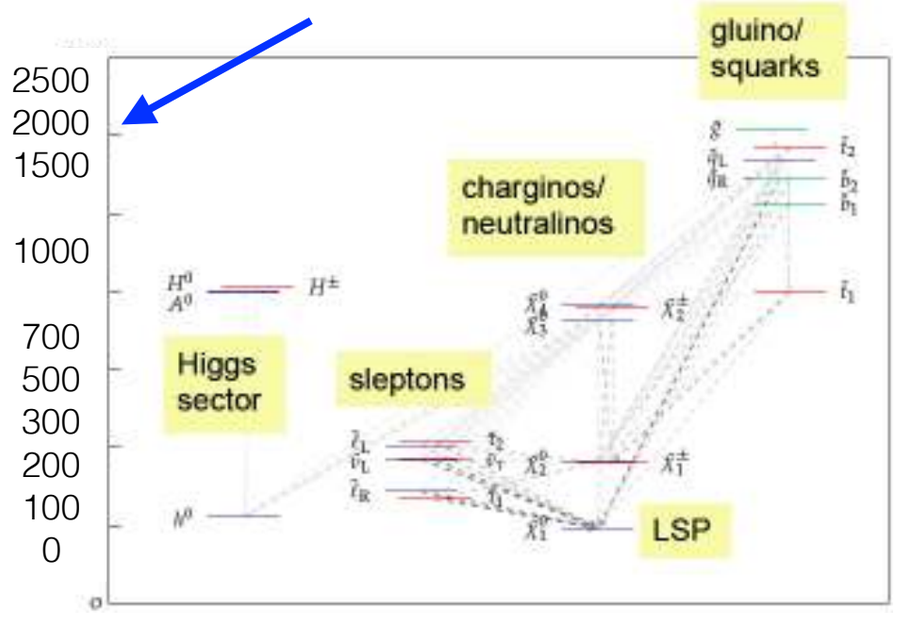
Supersymmetry is a dream of a unified theory of all particles and interactions



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

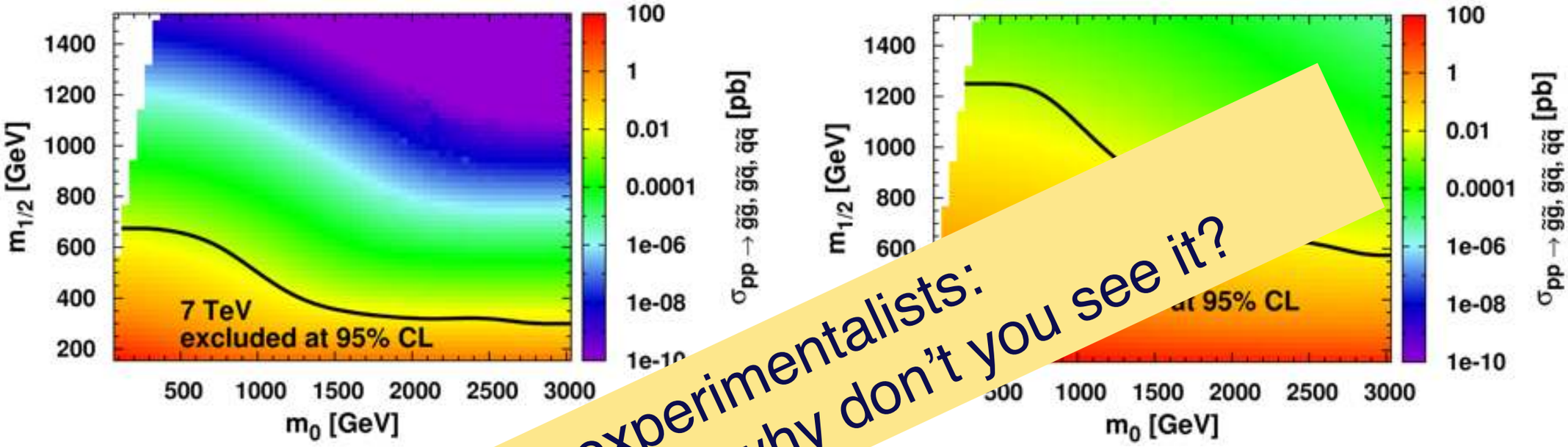
P.Sphicas

- Advent of the LHC: huge new ground within reach
- A search is defined by its signature and by its background estimation method.
- If SUSY is the answer to the "naturalness" problem, then there must exist light colored particles
- This is a crucial moment: either we find SUSY at the LHC eventually or we have to solve the hierarchy problem some other way! (which way?)



What is the LHC Reach?

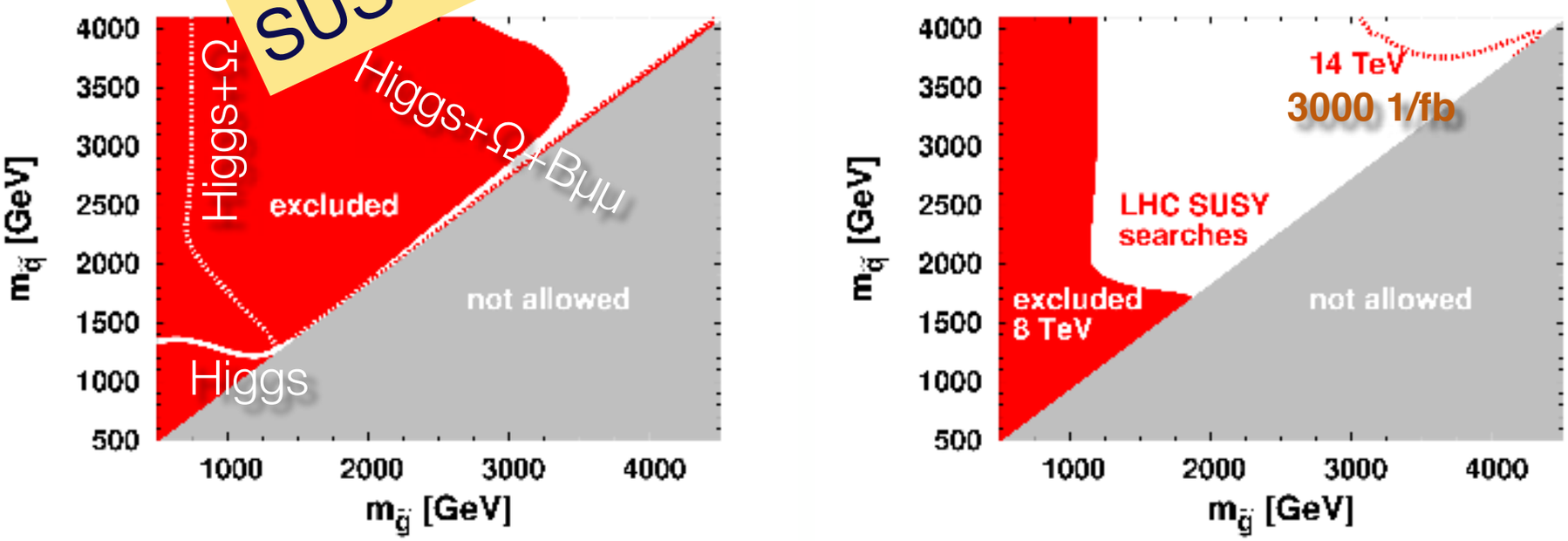
Universal scenario



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

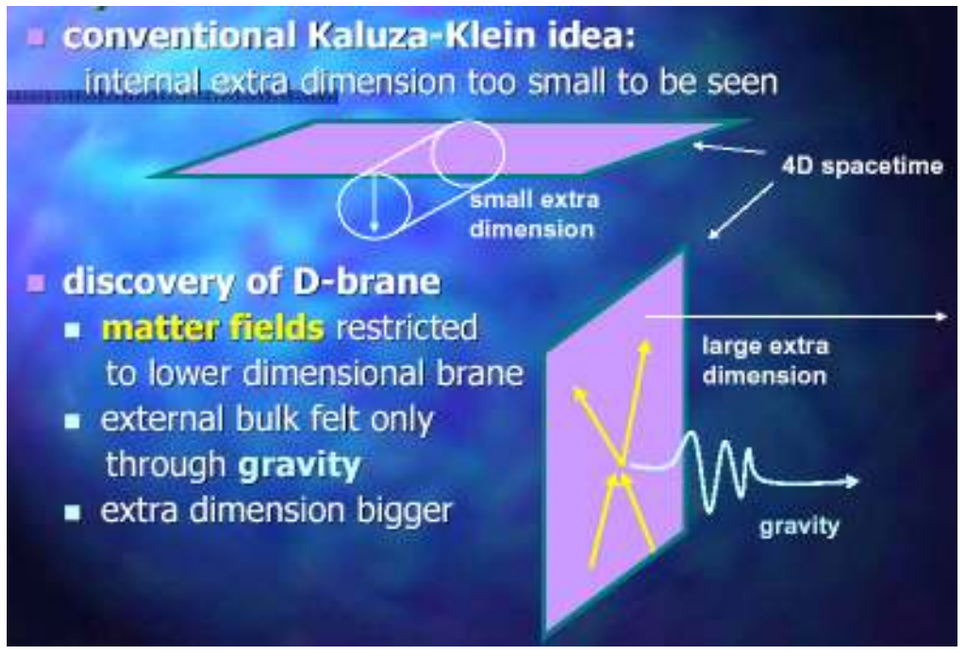
...perpartners

NMSSM



Search for New Physics

Extra Dimensions/ Exotics



Q: Do we really live on a brane?
A: We have to check it
Q: Do we have good reasons to believe in it?
A: No, but it is appealing
Q: Why D>4?
A: String theory loves it
Q: Is it what we believe in?
A: We believe in BIG deal

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

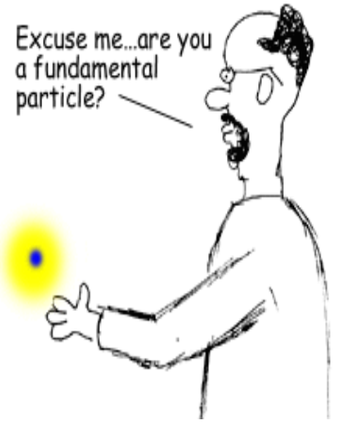
Exotics

- Leptoquarks
- Long-lived particles
- Off-pointing photons
- Excited fermions
- Contact interactions

Drawback: No real motivation -> Unknown scale

Search for New Physics

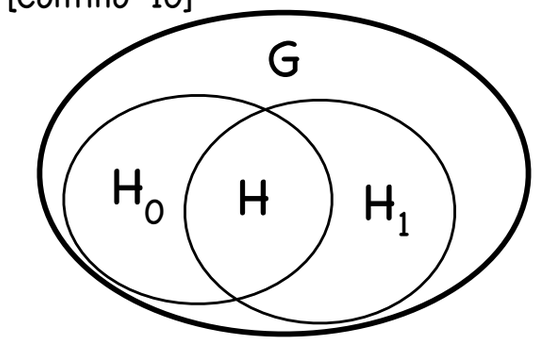
Compositeness



New level of fundamental particles

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

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

Concluding Remarks

- ☑ LHC experiments are at the front line of mystery land: be patient
- ☑ Target #1: Higgs sector
- ☑ Target #2: Dark Matter
- ☑ Target #3: New physics (supers
- ☑ Future developmen ucially depends on LHC outcome
- ☑ Compli rches 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

I bet that discoveries will come!