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

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?

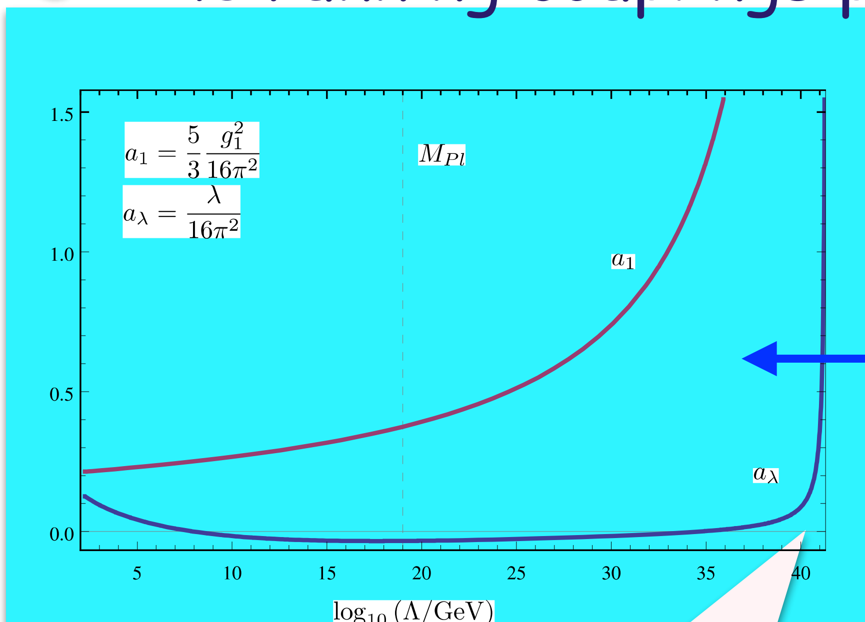
- why the SU(3)xSU(2)xU(1) ?
- why 3 generations ?
- why quark-lepton symmetry?
- why V-A weak interaction?
- why L-R asymmetry?
- why B & L conservation?
- etc

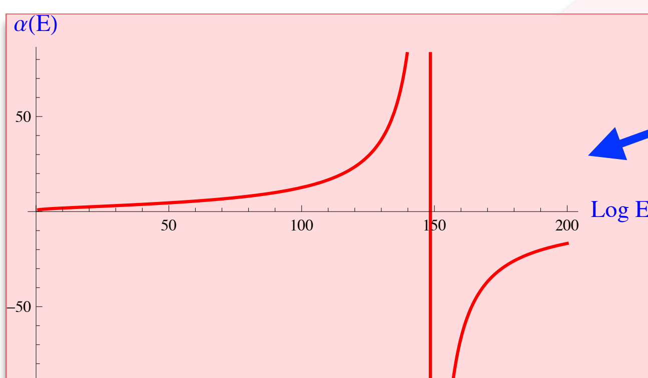
How's?

- 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

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

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

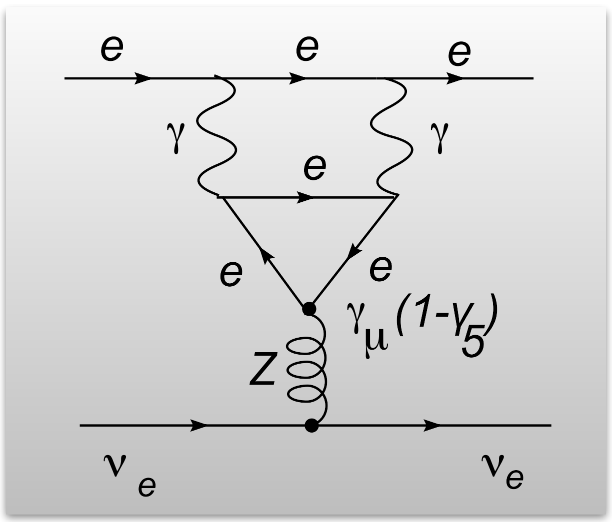
- The situation may change in GUTs due to new heavy fields @ the GUT scale

- requires modification of the ST at VERY high energies

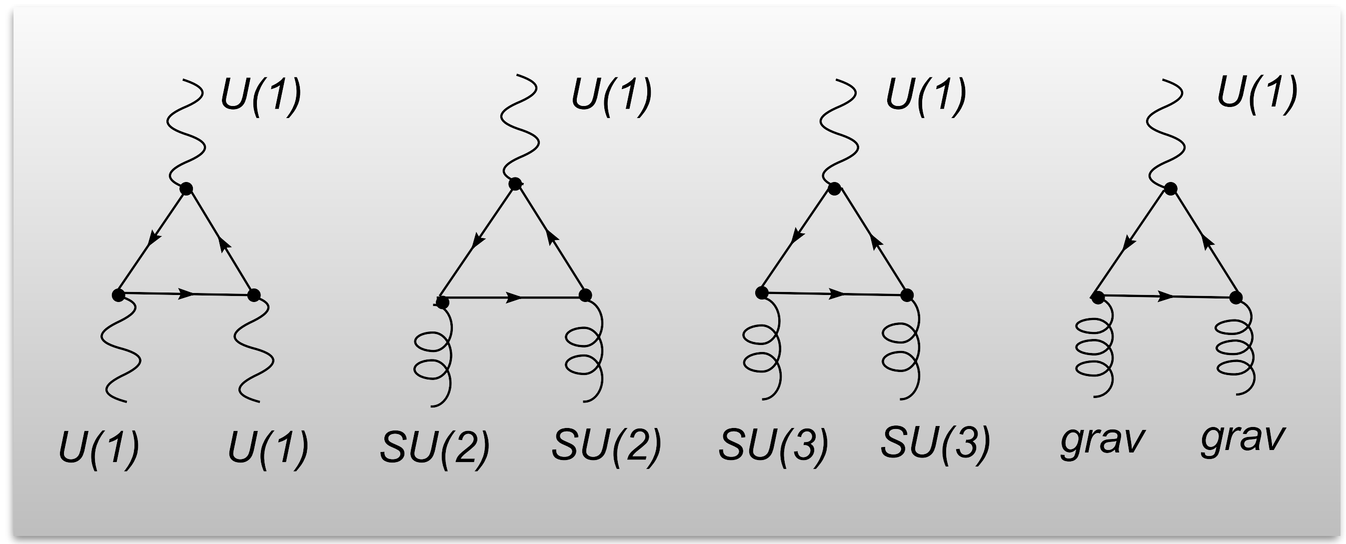
Is the SM consistent quantum field theory?

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

This is the anomalous diagram



Anomalies in the SM



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

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

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

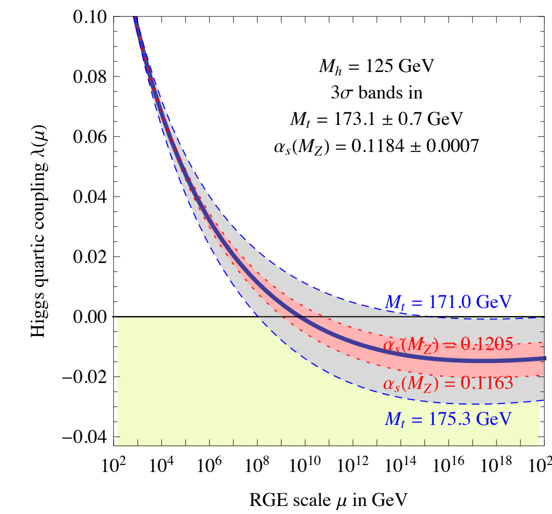
$$\begin{aligned} TrY_L &= 3\left(\frac{1}{3}+\frac{1}{3}\right) - 1 - 1 = 0, \\ TrY_q &= 3\left(\frac{1}{3}+\frac{1}{3}-\frac{4}{3}-(-\frac{2}{3})\right) = 0, \\ TrY &= 3\left(\frac{1}{3}+\frac{1}{3}-\frac{4}{3}-(-\frac{2}{3})\right) - 1 - 1 - (-2) = 0. \end{aligned}$$

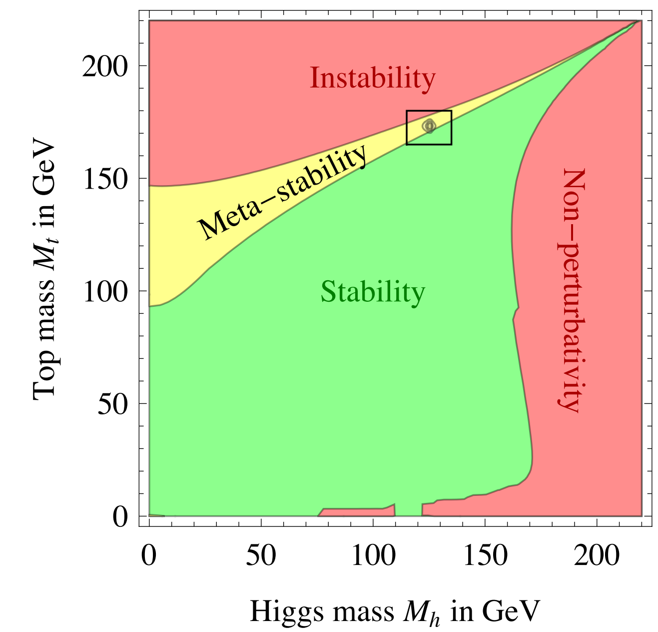
- cancellation of anomalies requires quark-lepton symmetry
- this is a hint towards the Grand Unified Theories

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





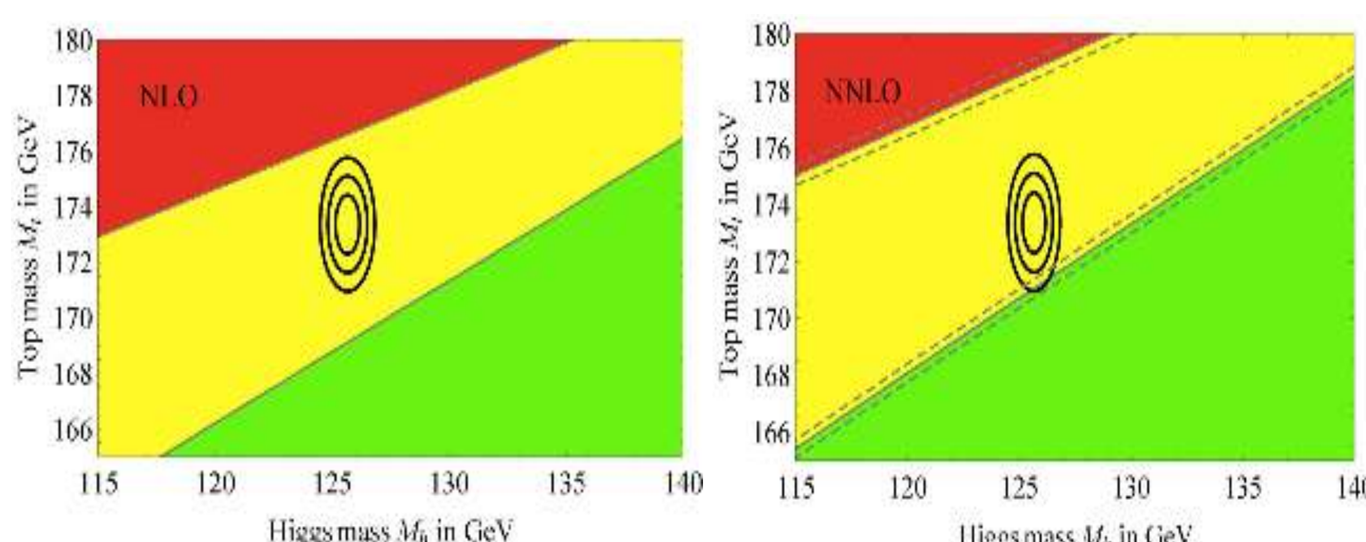
The way out might be the new physics at higher scale:

- 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

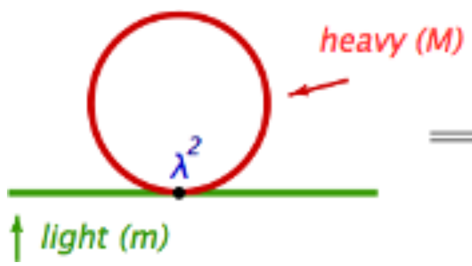


Espinosa'13

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



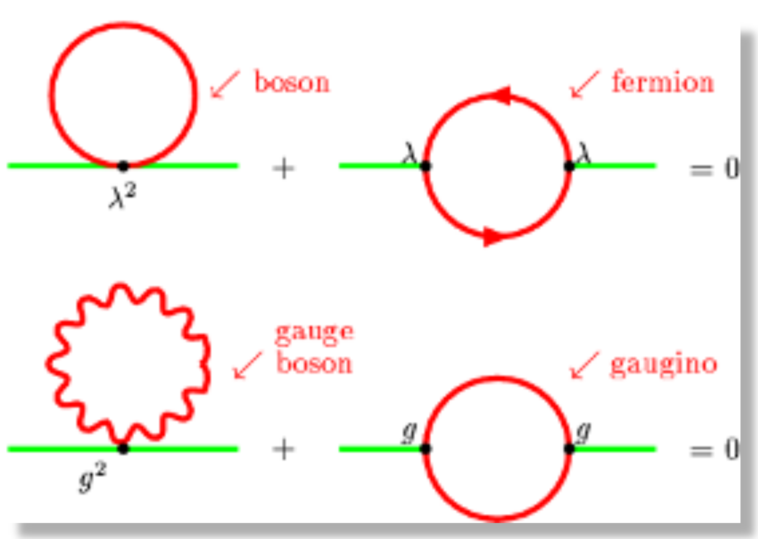
$\delta m^2 \sim \lambda^2 \cdot M^2$

$\sim 10^2 \quad \sim 10^{-1} \quad \sim 10^{16}$

- 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

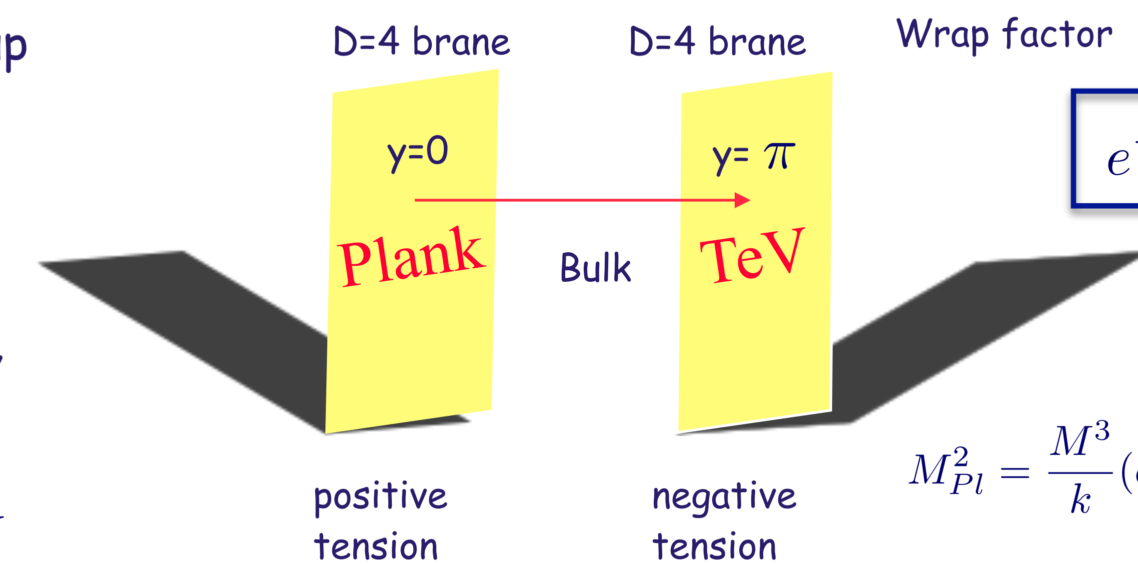
- the way out might be the new physics at higher scale:

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:



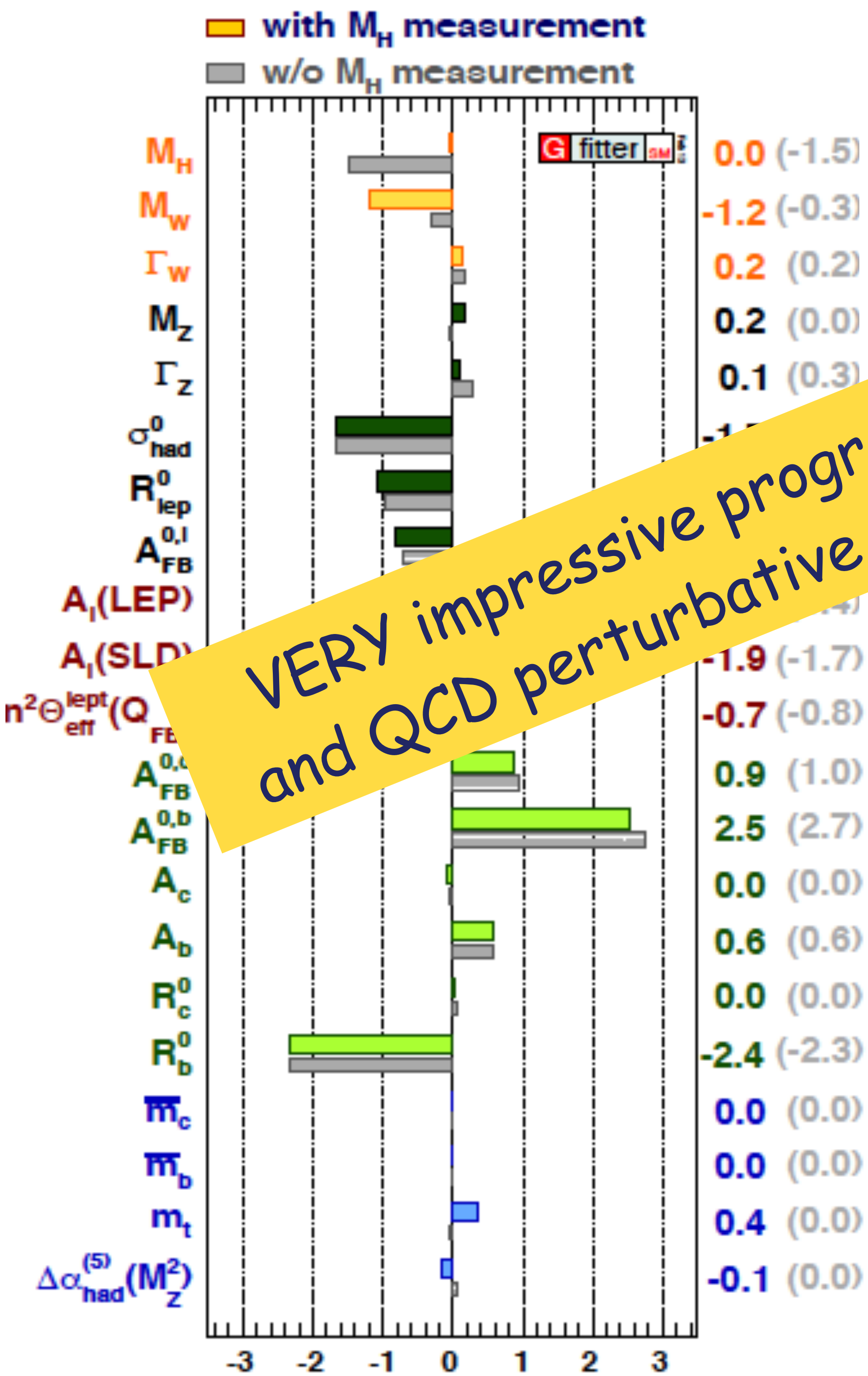
Wrap factor

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

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

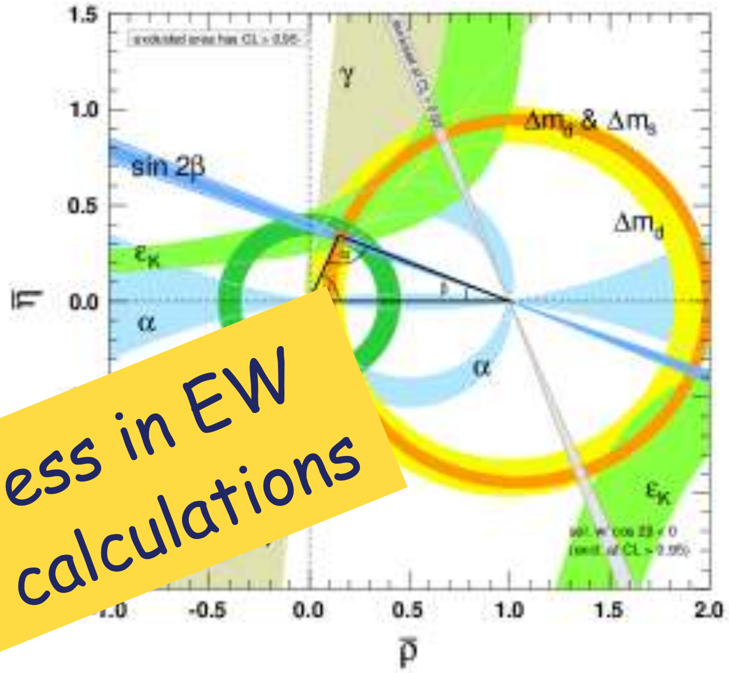
Does the ST describes all experimental data?

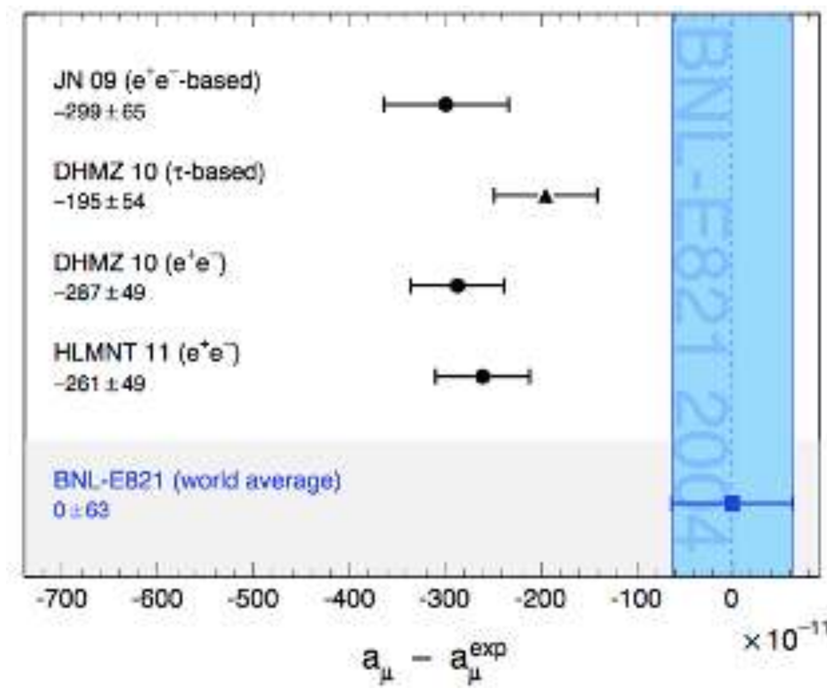
- EW observables pool



VERY impressive progress in EW and QCD perturbative calculations

- Flavour Physics observ





- 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

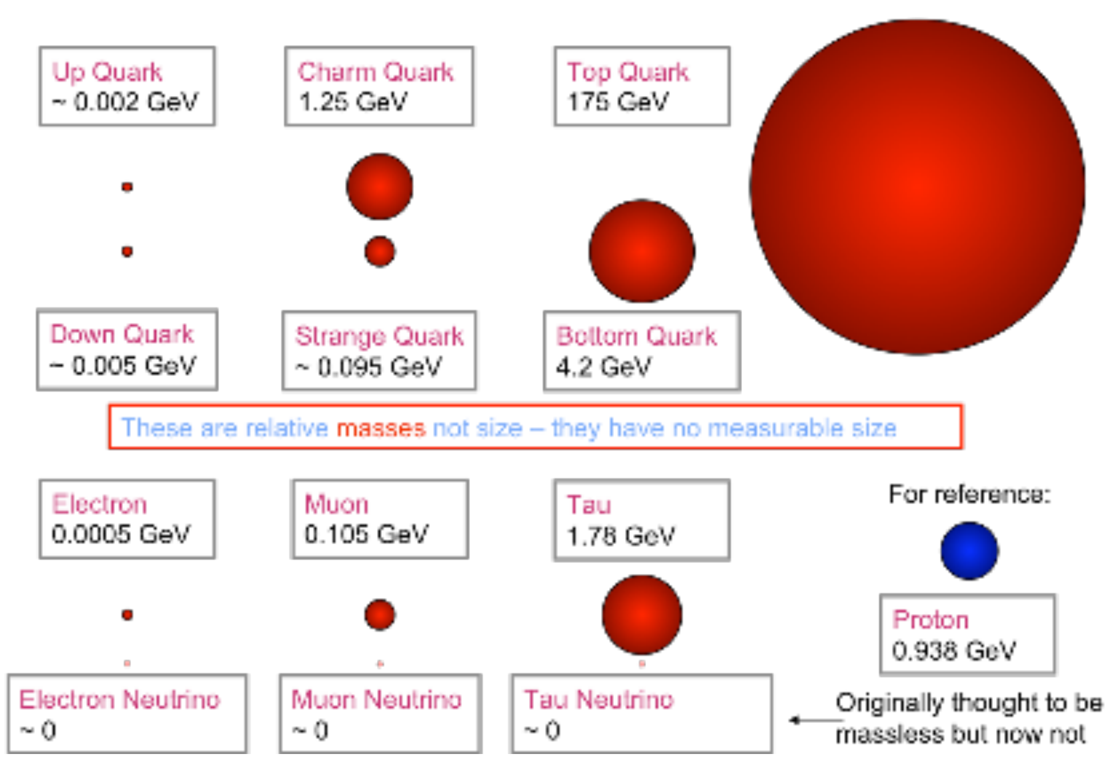
- strong CP problem: axion field ?
- rare decays: fine so far
- spin crisis in QCD: parton distributions?
- neutrino masses and mixings: looks OK but still needs to be clarified

The Mass Spectrum and Mixing

- Mass spectrum?

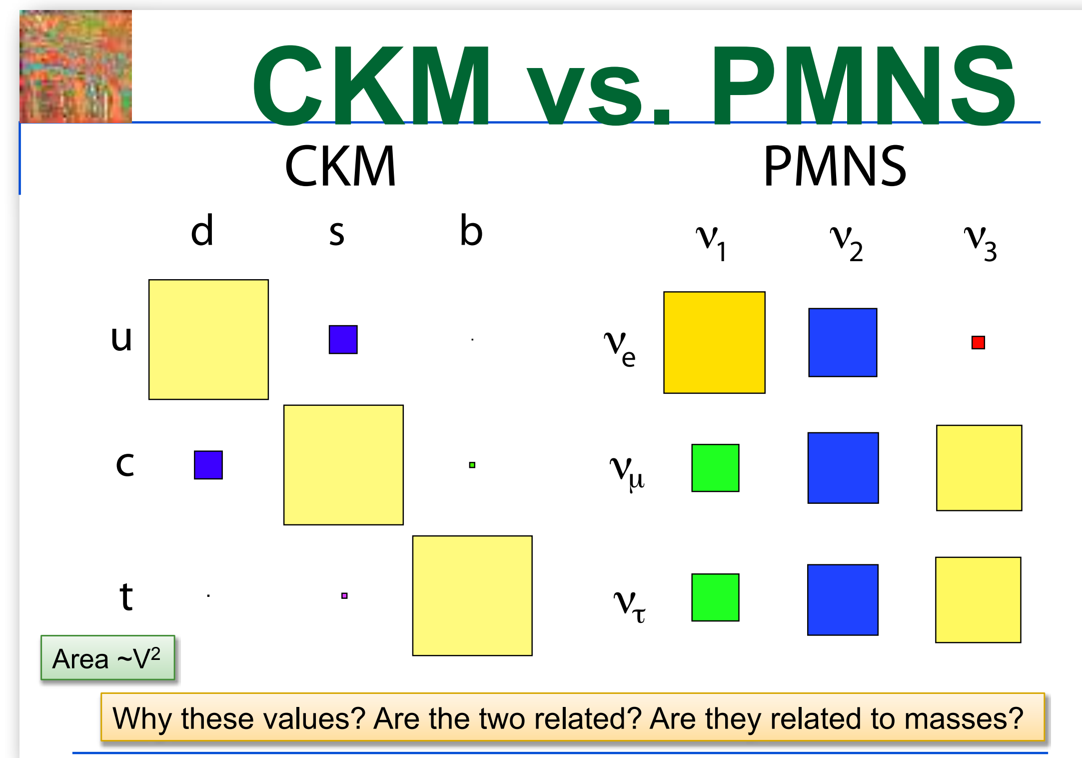
$$m_{quark} = y_{quark} \cdot v$$
$$m_{lepton} = y_{lepton} \cdot v$$
$$m_W = g/\sqrt{2} \cdot v$$
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$
$$m_H = \sqrt{\lambda} \cdot v$$
$$m_\gamma = 0$$
$$m_{gluon} = 0$$

SM



- Mixing Matrices?

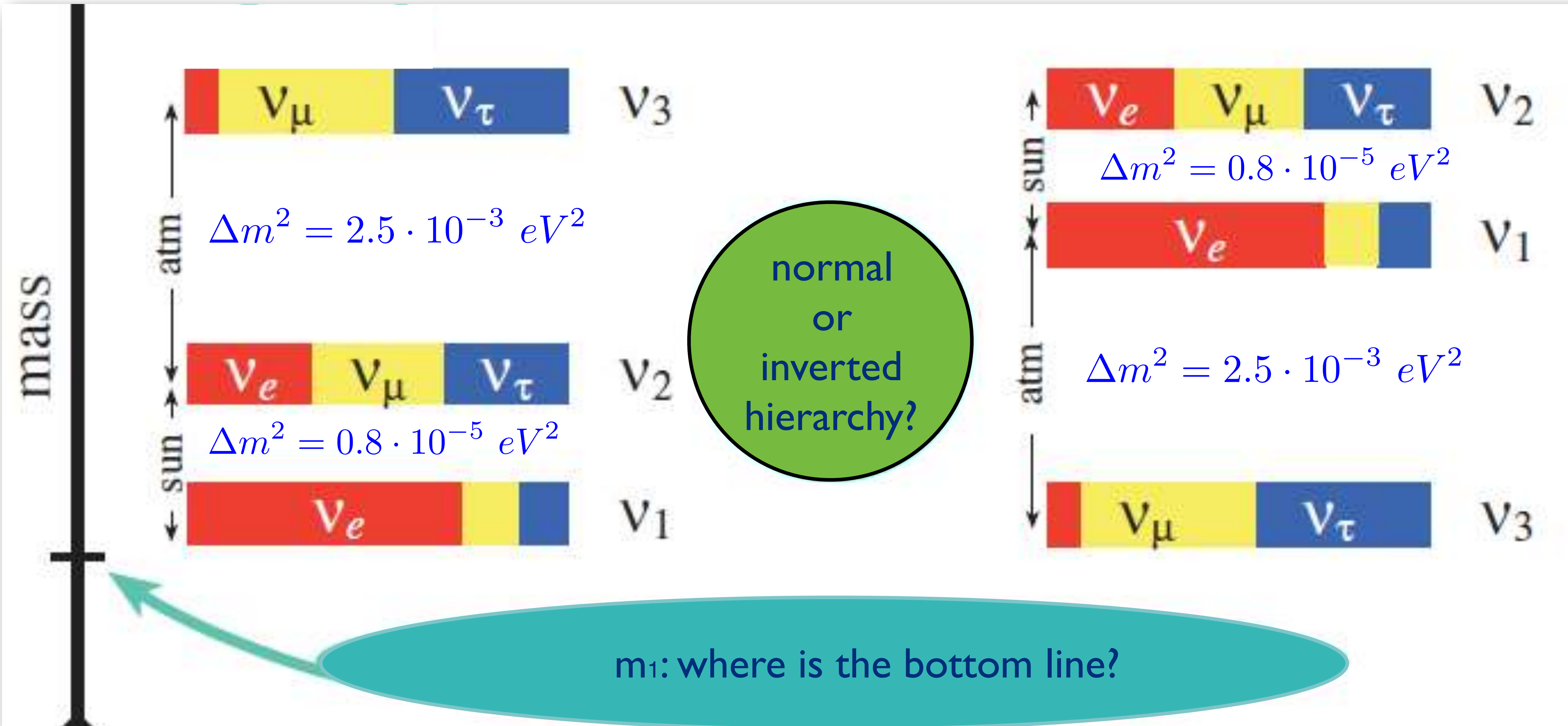
- Quark-Lepton Symmetry
- Strong difference in parameters



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

Neutrino Sector

Neutrino masses



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

cosmology: the CMB spectrum

Planck

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

β-decay

Troitsk-Mainz

→

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

KATRIN

Neutrino Sector

Dirac or Majorana?

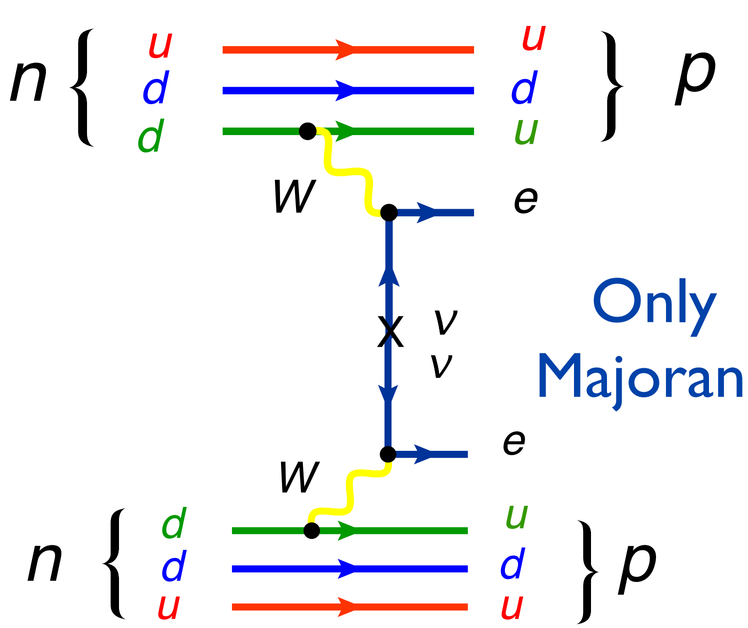
$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}$$

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

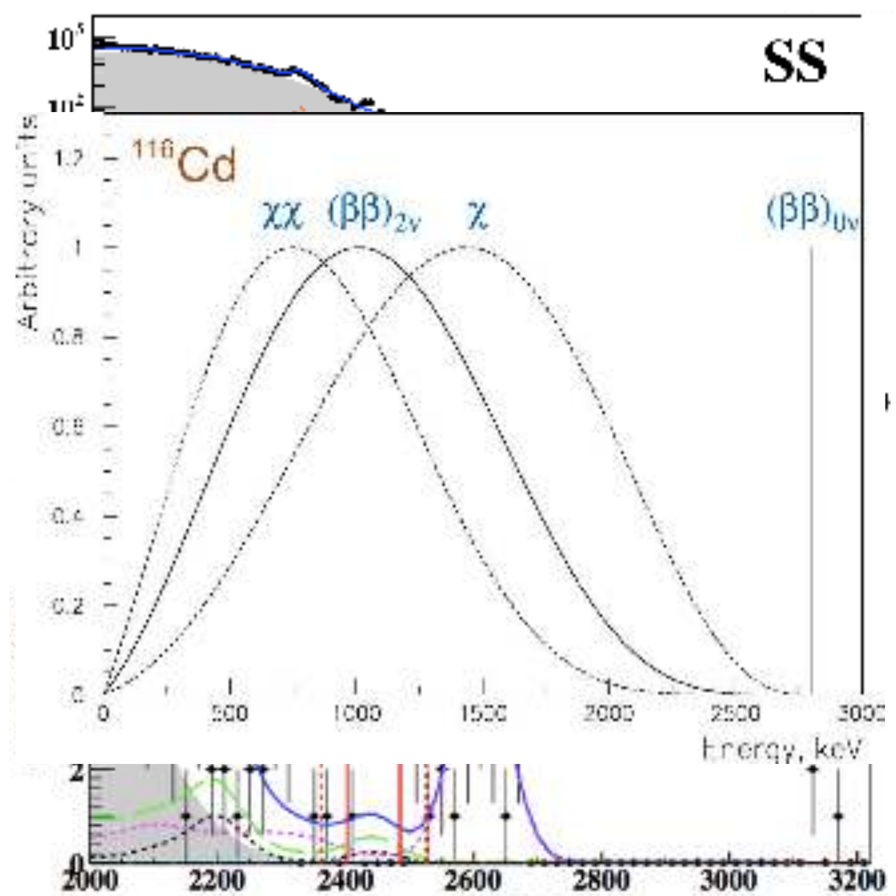
?

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

0νββ decay



Only Majorana

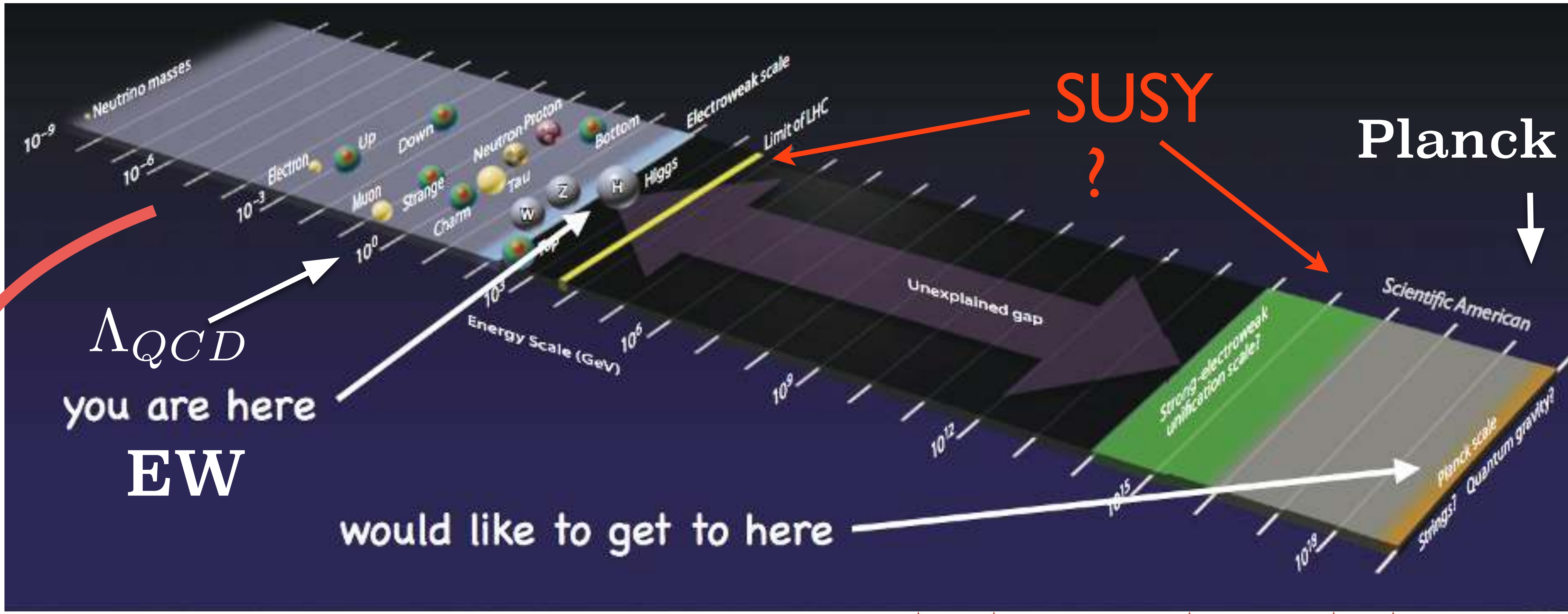


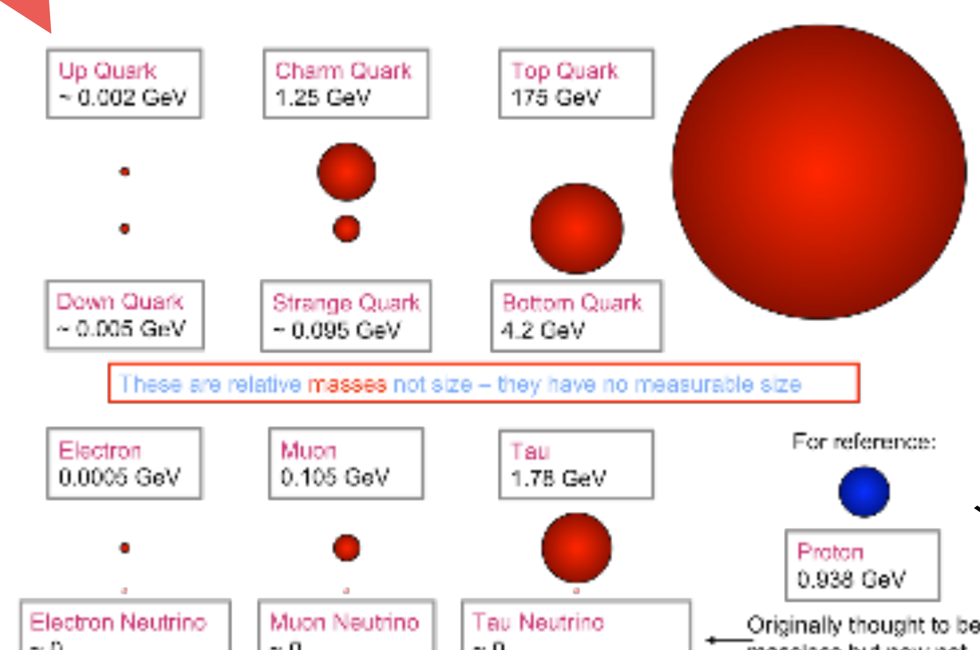
Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

$T_{1/2}2\nu\beta\beta$ (^{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?





?

Vacuum Stab ~ 10^{11}GeV

Majorana scale ~ 10^{12} GeV

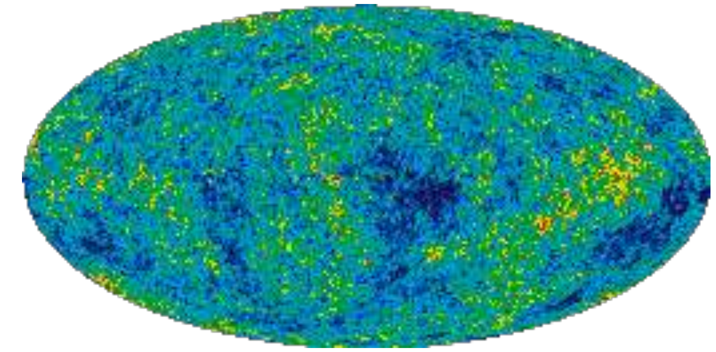
GUT scale ~ 10^{16}GeV

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 $\not{C}\not{P}$ than in the SM

- Relic abundance of the Dark Matter

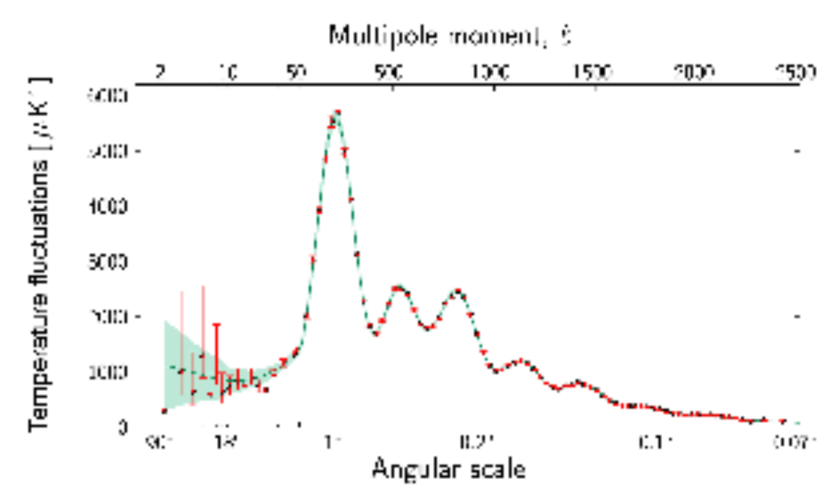
$$OM = 4.9\%,\ DM = 26.8\%,\ DE = 68.3\%$$

- 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

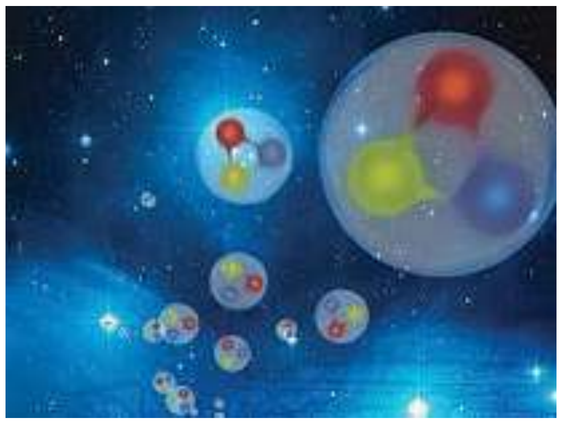
$$\Sigma m_\nu\ [eV] < 1.11(0.22)$$
$$Planck + WP + lensing + HST$$

- Probably a hint towards new physics

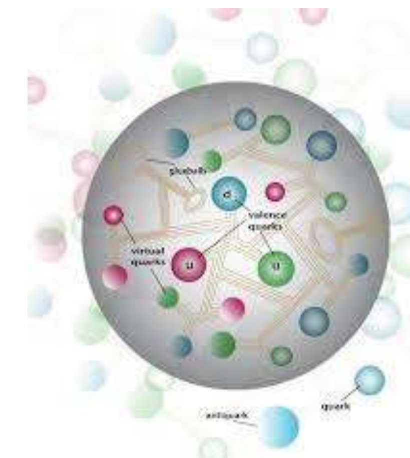
Do we understand confinement?

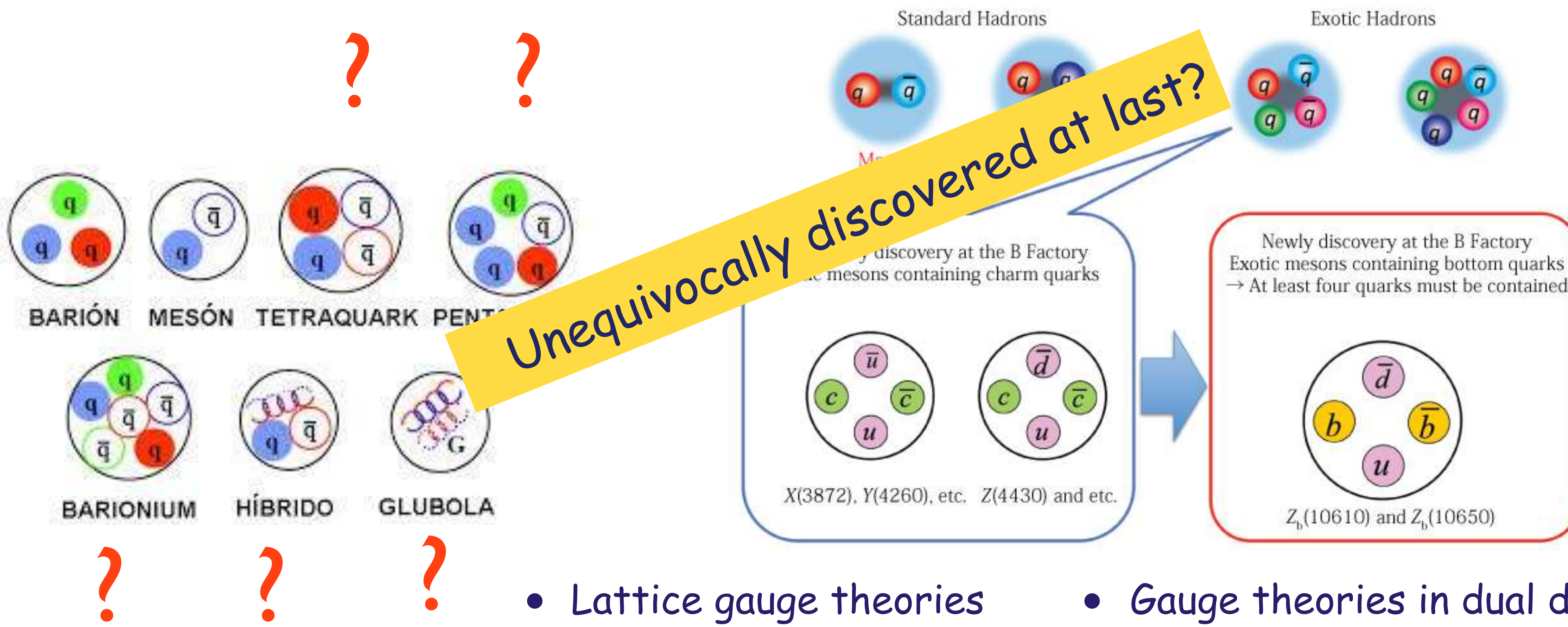
Challenging problem in particle physics well inside the SM

Time to come back?



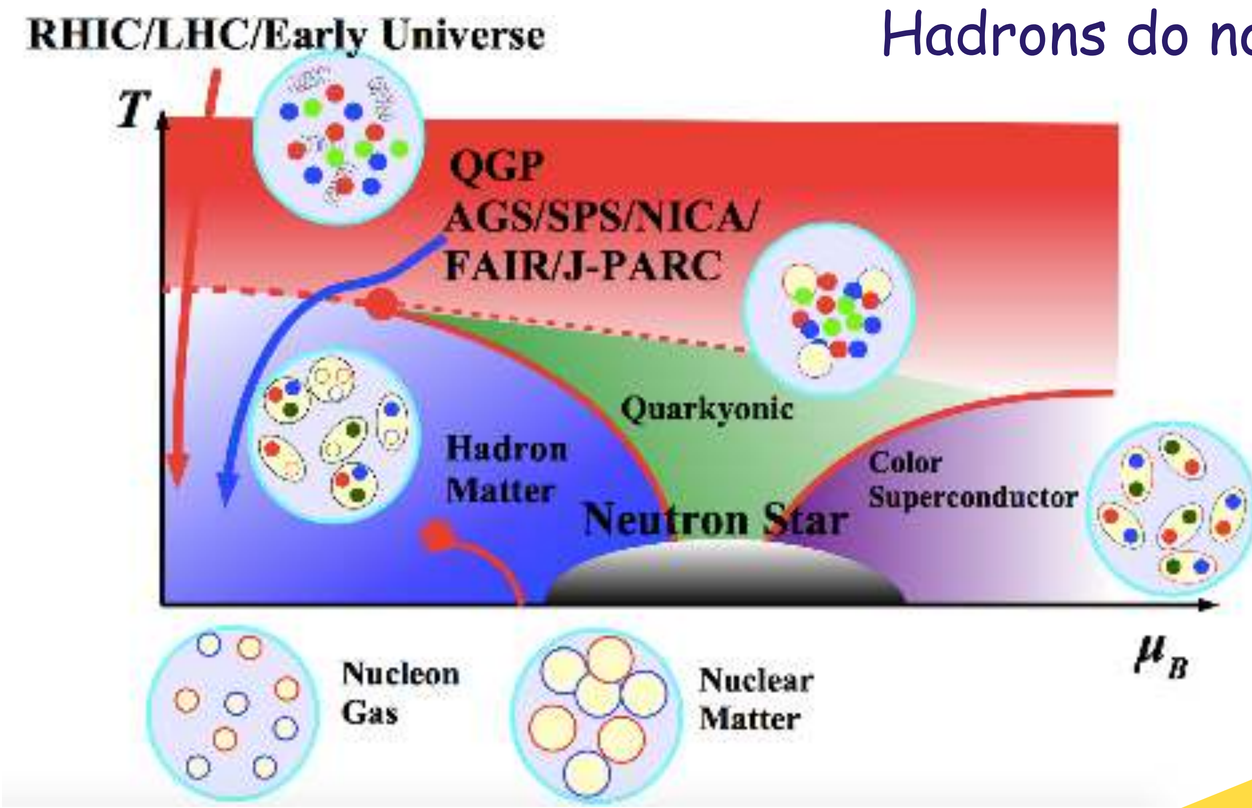
- How confinement actually works?
- Why colourless states?
- Which bound states exist in Nature?





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

Dense hadron matter - new phase?

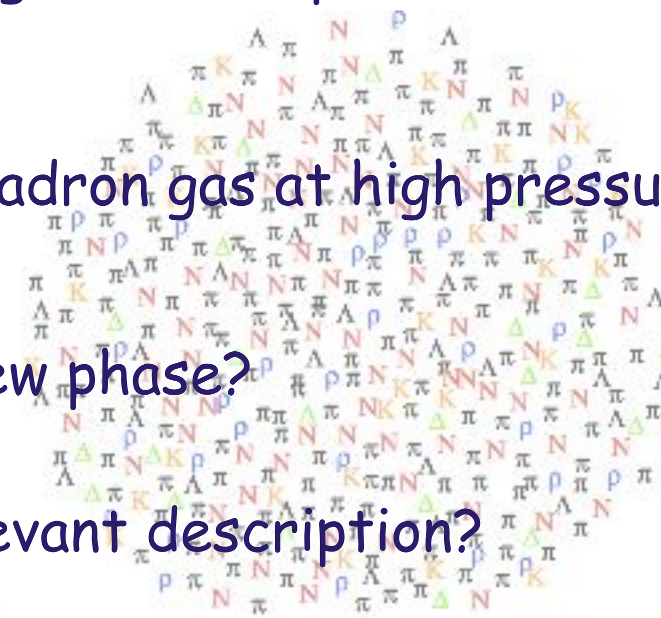


Hadrons do not exist above the Hagedorn temperature

What happens with hadron gas at high pressure?

How to get the new phase?

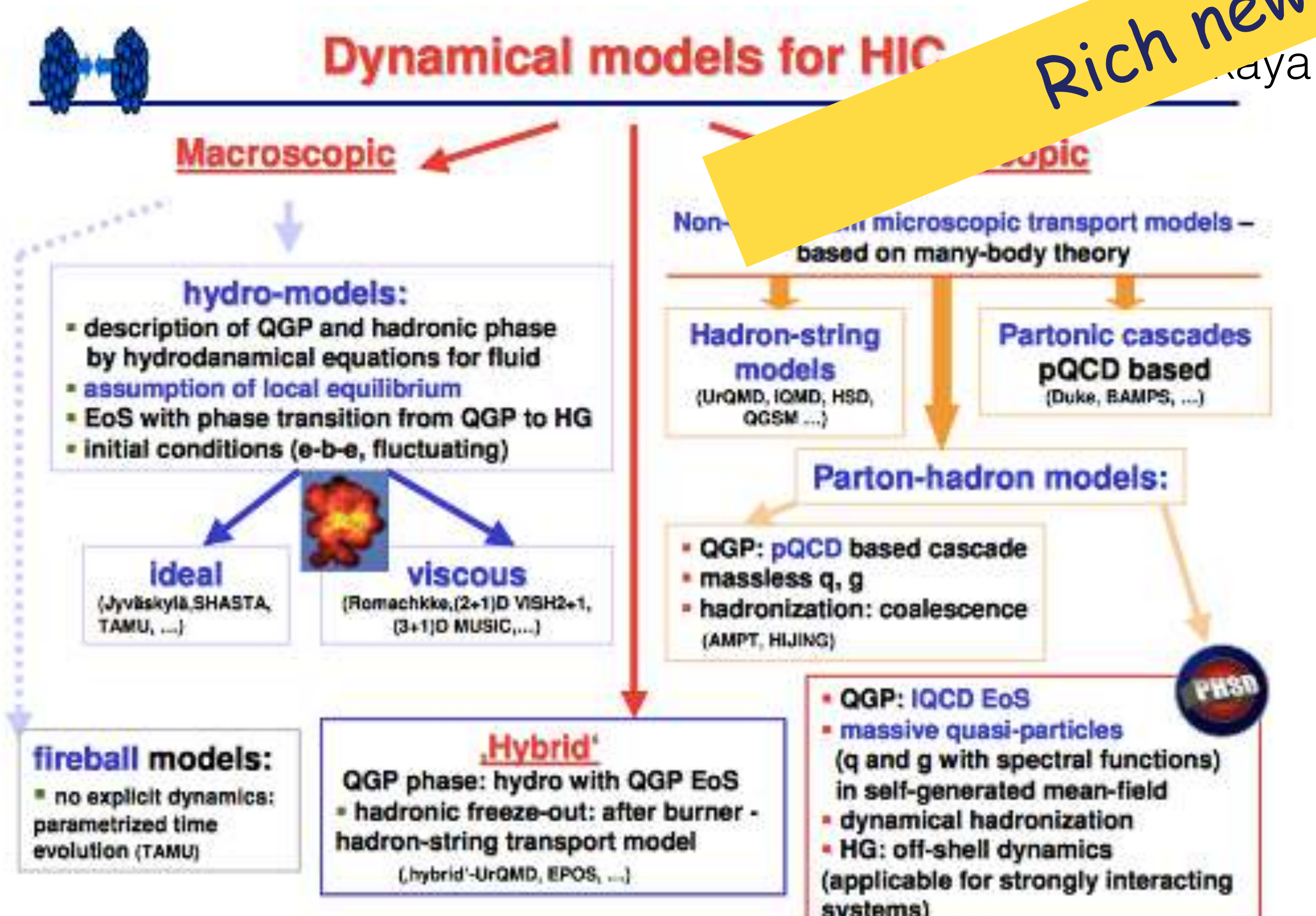
What is the relevant description?

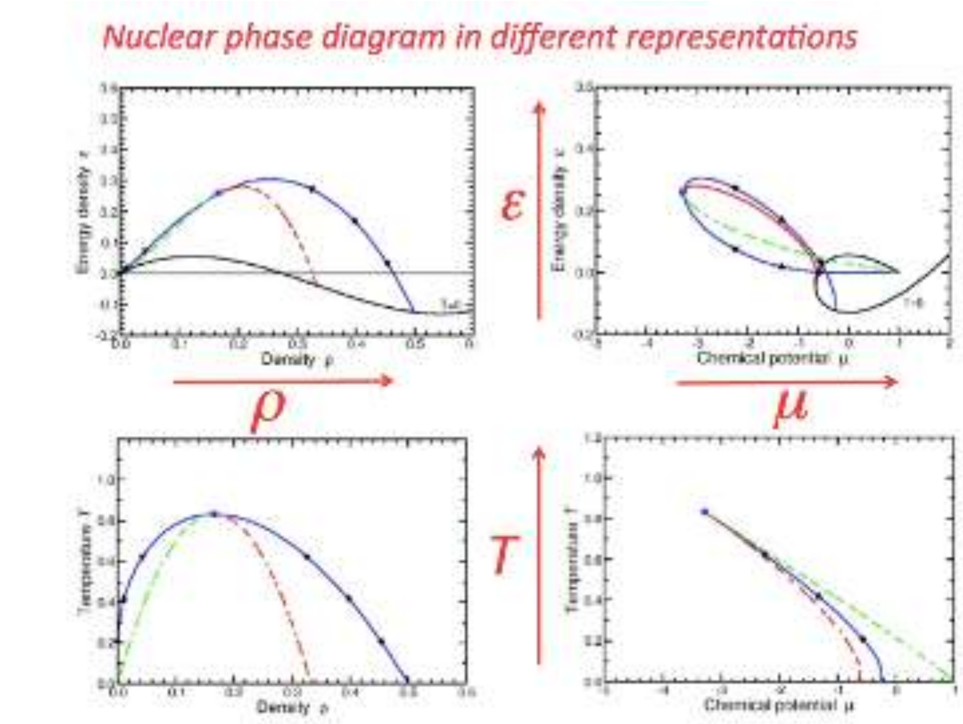


J.C. and H. Satz, Z. fuer Physik C57, 135, 1993.

Rich new phenomena

stical 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

<u>Custodial symmetry as guiding principle for extensions</u>

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

indicates that an approximate global symmetry exists,

broken by the vev to the diagonal 'custodial' symmetry

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

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

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

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 …

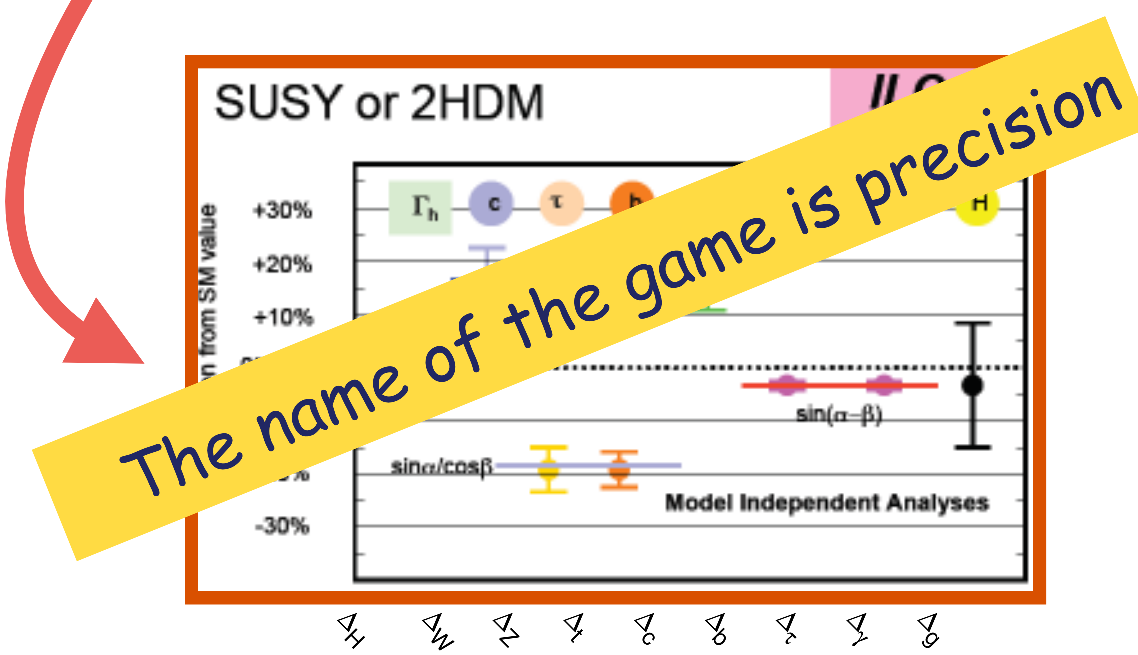
Search for New Physics

The Higgs Boson - Target # 1

Is it the SM Higgs boson or not?

How to probe?

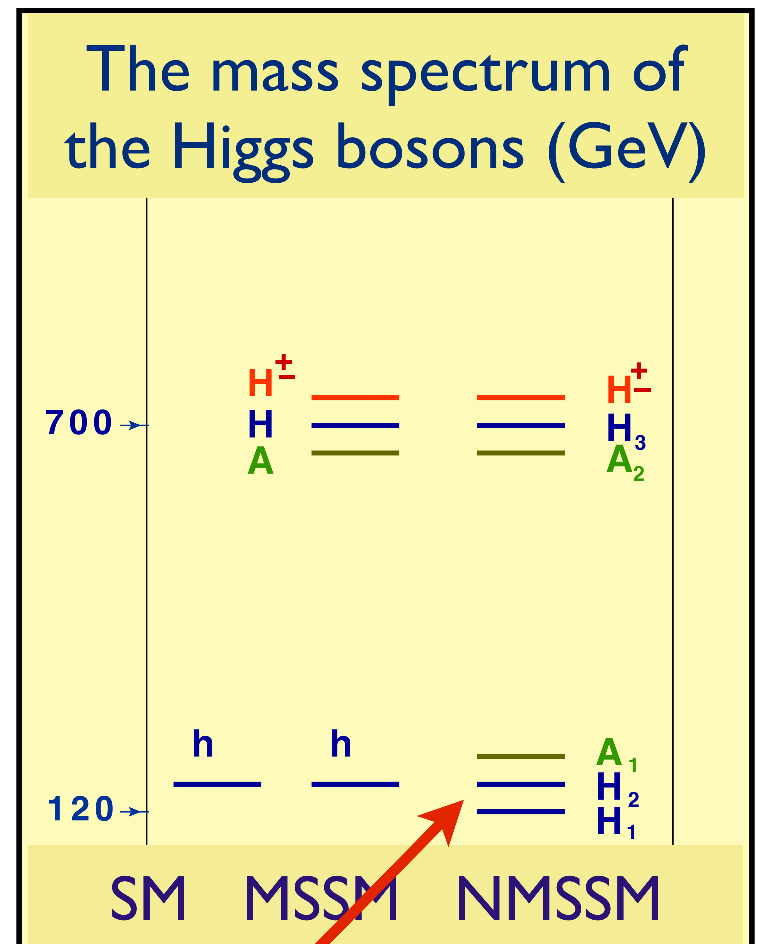
- Probe deviations from the SM Higgs couplings



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

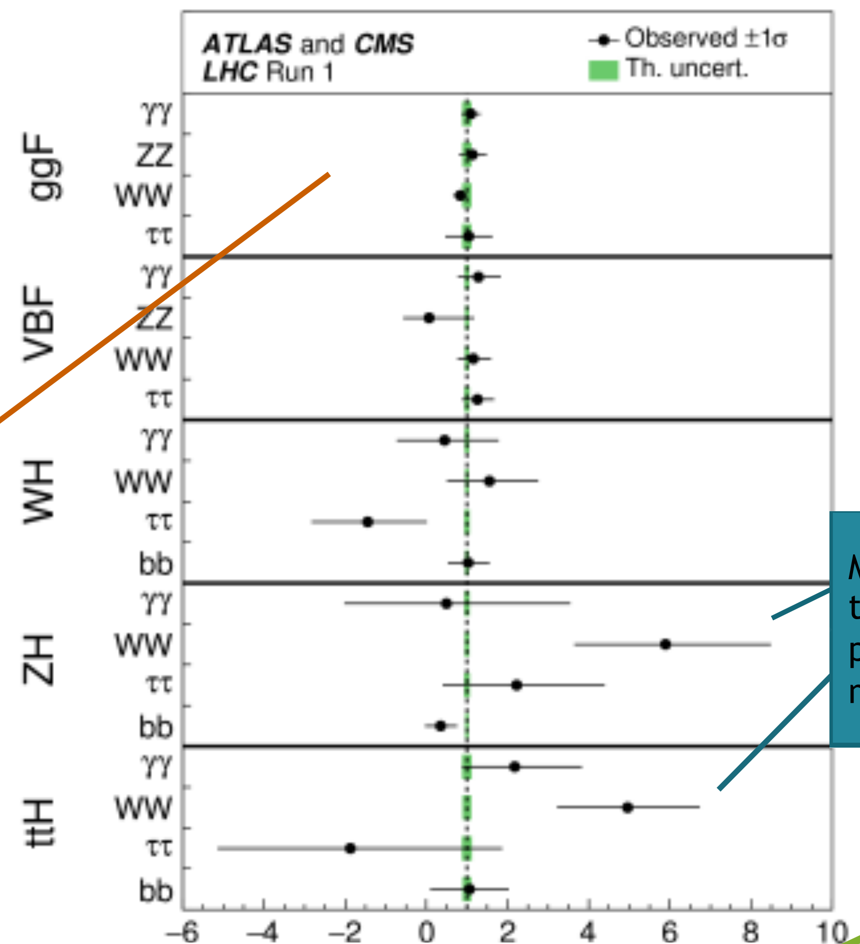
- The Higgs physics has already started
- This is the task of vital importance.
- May require the electron-positron collider

- Perform direct search for additional scalars



We may have found one of these states

Higgs Boson (125)



Precision test of Higgs boson coupling strength

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

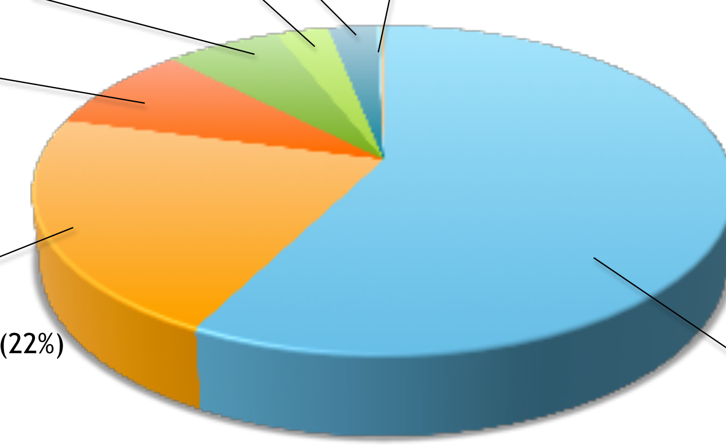
Mild excess in ttH and ZH production modes

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

– Mass has been measured to 0.2% precision
m_H=125.09±0.24 GeV

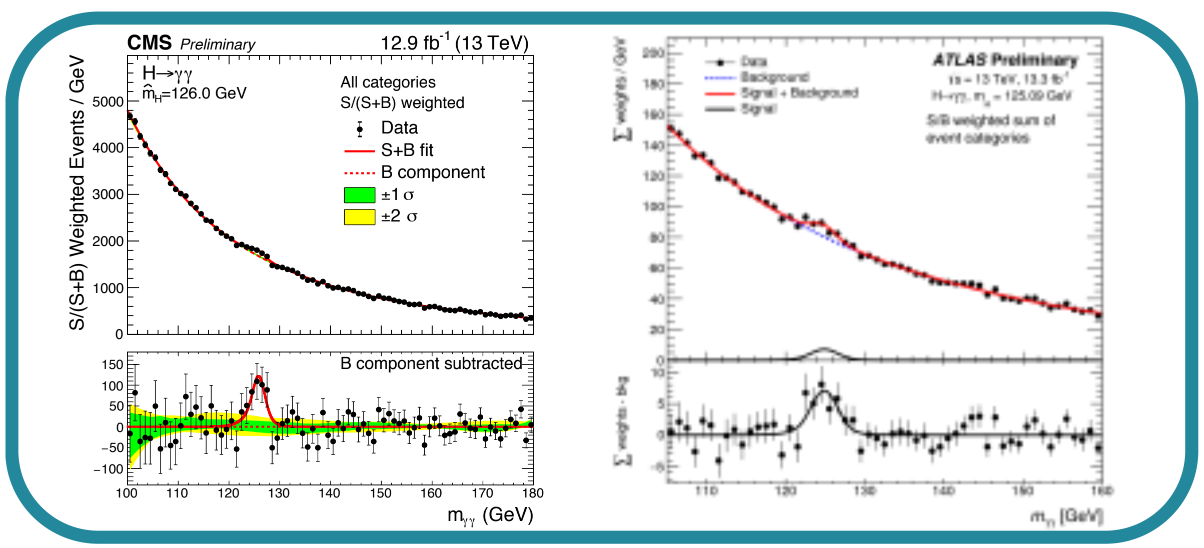
– Angular distributions consistent with spin 0 and even parity

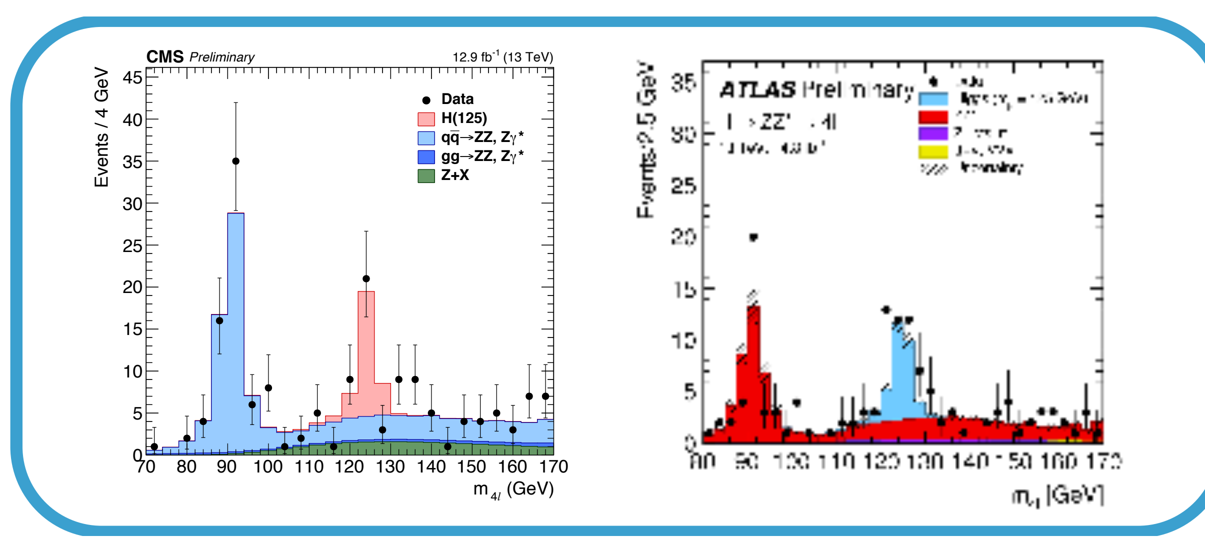
– All couplings are consistent with SM within 2.5σ



Observed decay modes: γγ, ZZ, WW, ττ

Missing bb,cc, μμ, Zγ



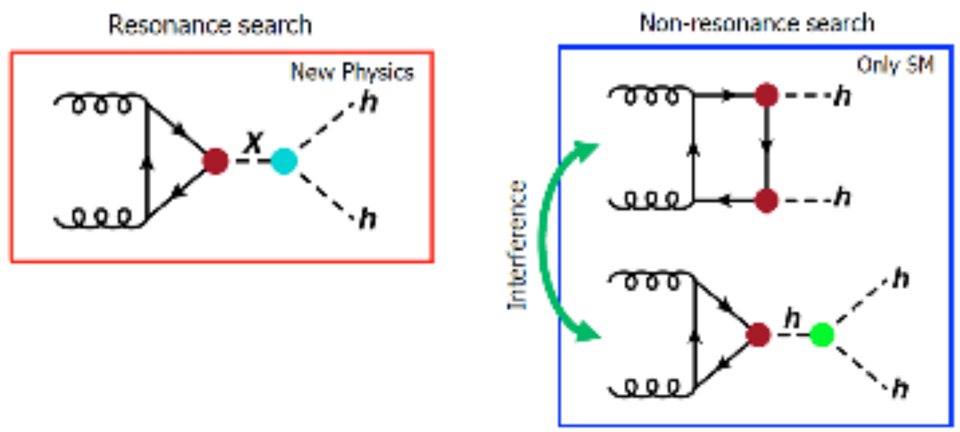


Higgs→γγ

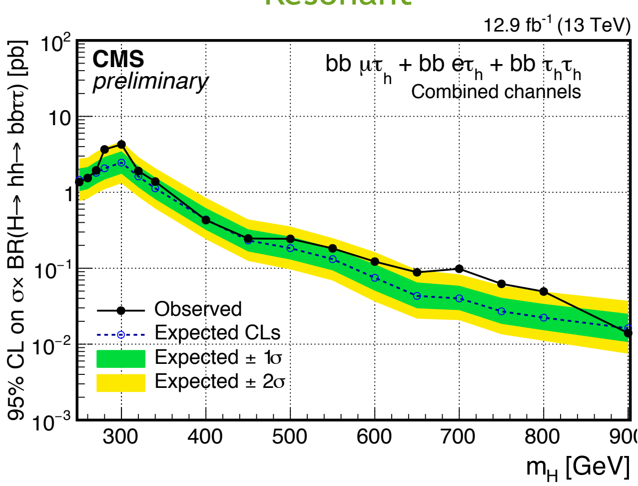
Higgs→ZZ*

Extra Higgs Bosons

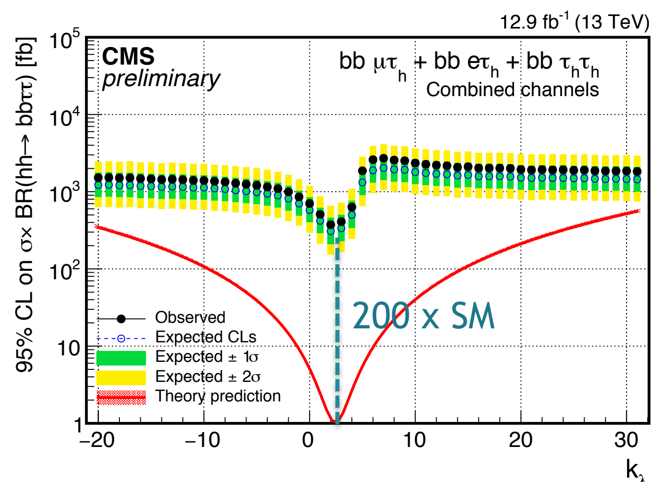
Higgs→hh→bbττ



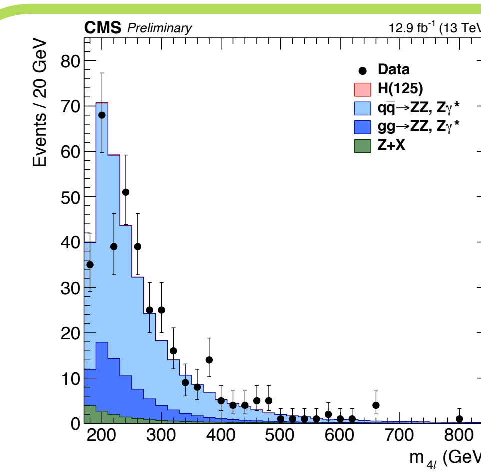
Resonant

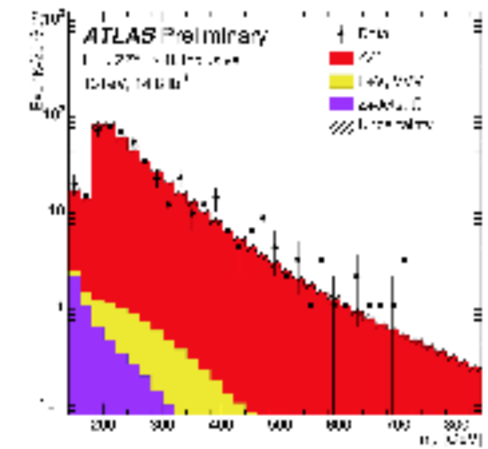


Non-Resonant

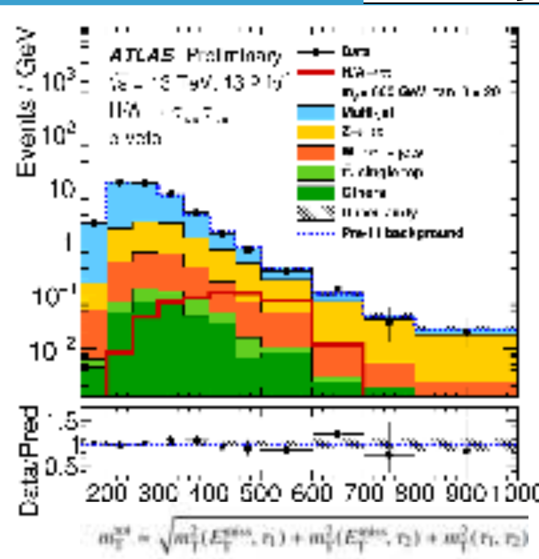


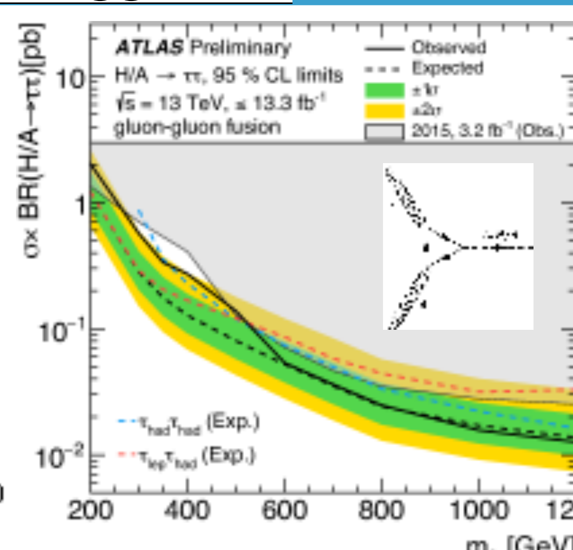
Heavy Higgs→ZZ→4l





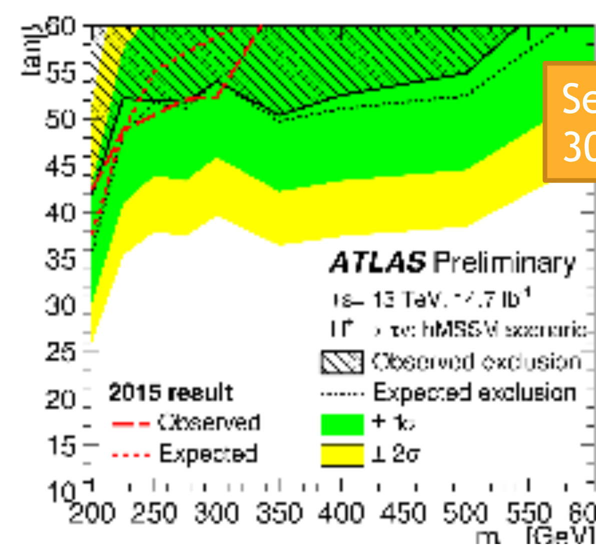
Heavy Higgs→ττ



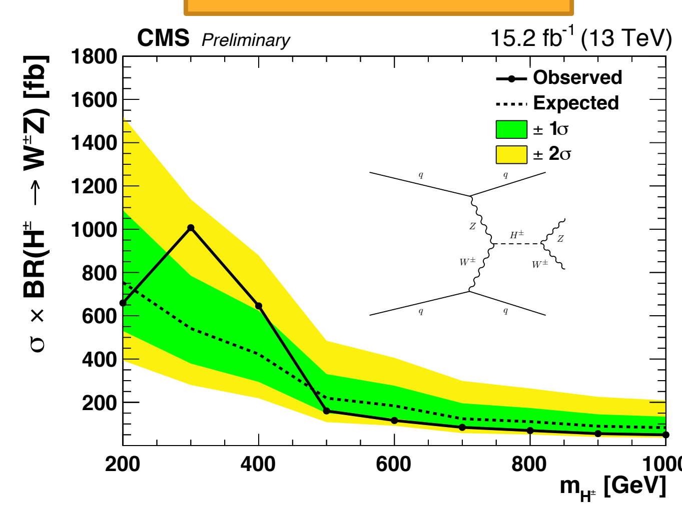


Charged Higgs

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



Search for H±WZ



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 favorable but possible

Not from the SM

- axion (axino)
- neutralino
- sneutrino
- gravitino
- heavy photon
- heavy pse... ...tone
- light sterile ...iggs

mSUGRA

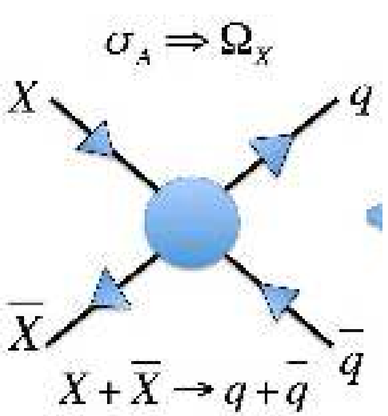
might be invisible (?)
detectable in 3...
less the... ...e
... undc...
pos... ...t
... the other
...odels

WIMP is our chance !

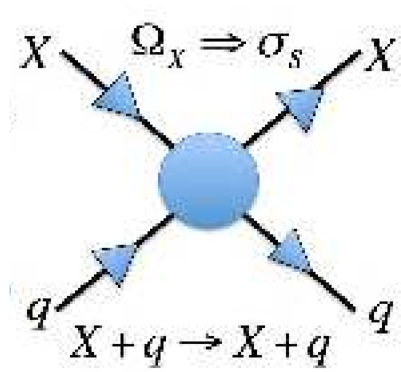
But we have to look elsewhere !

WIMP

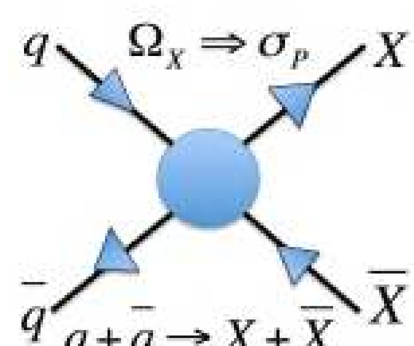
Annihilation in the halo



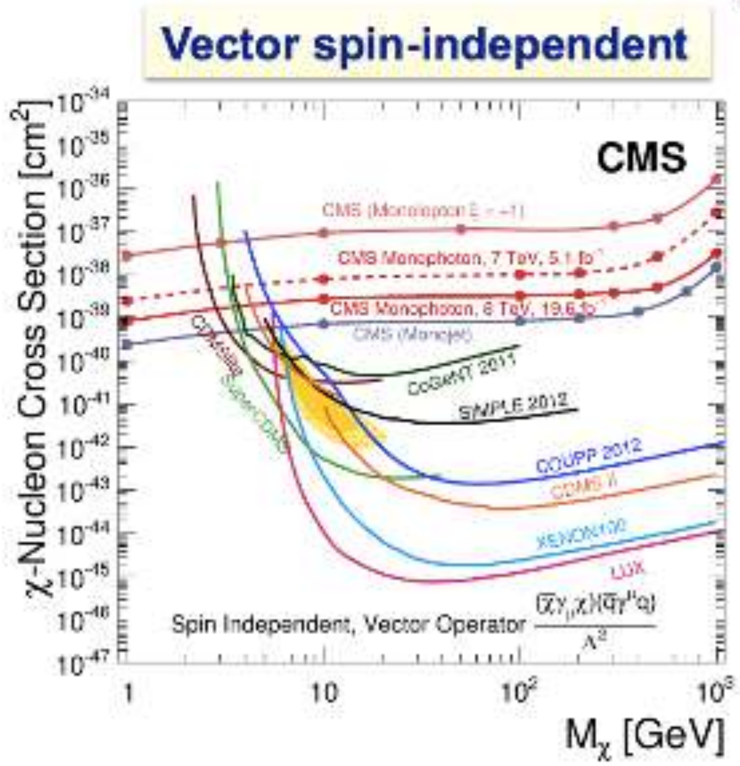
Scattering on a target



Creation at the LHC



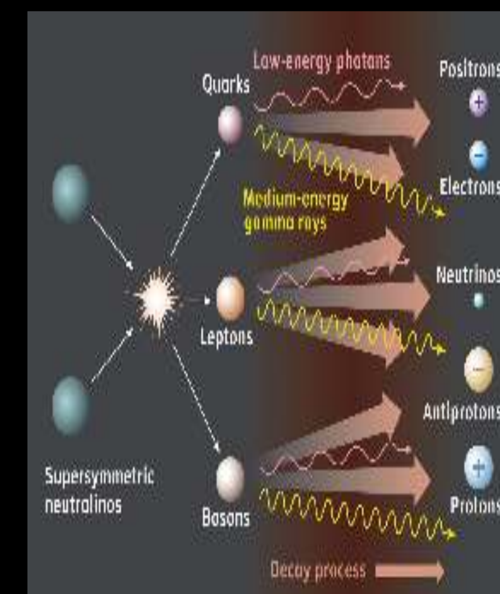
DM Searches



- Already close to neutrino floor
- Still have a chance

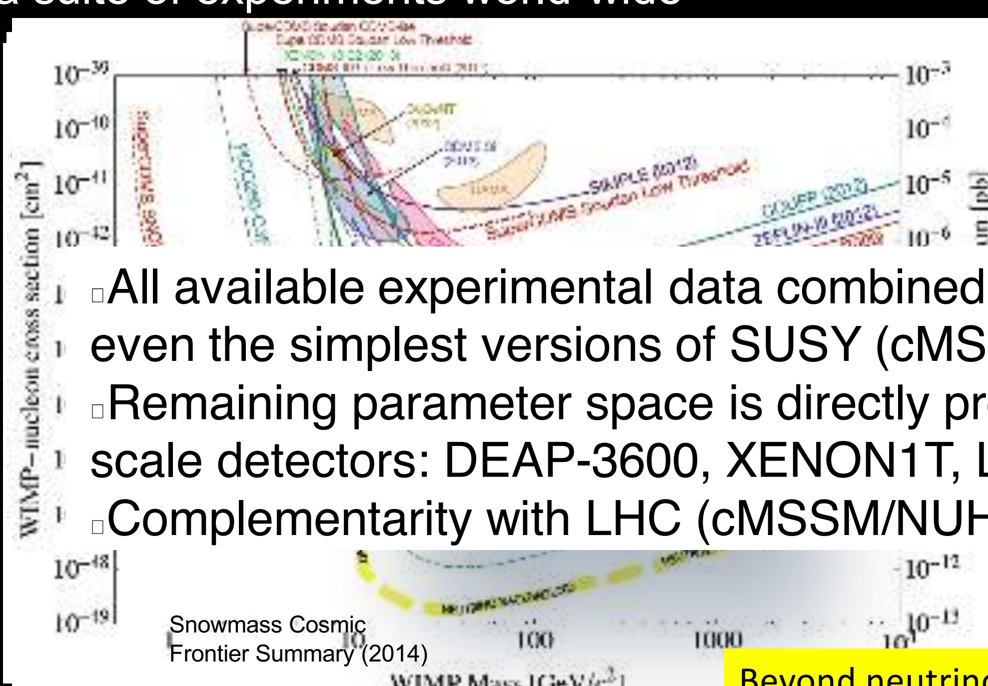
INDIRECT DETECTION

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



DIRECT DETECTION: STATUS AND PROSPECTS

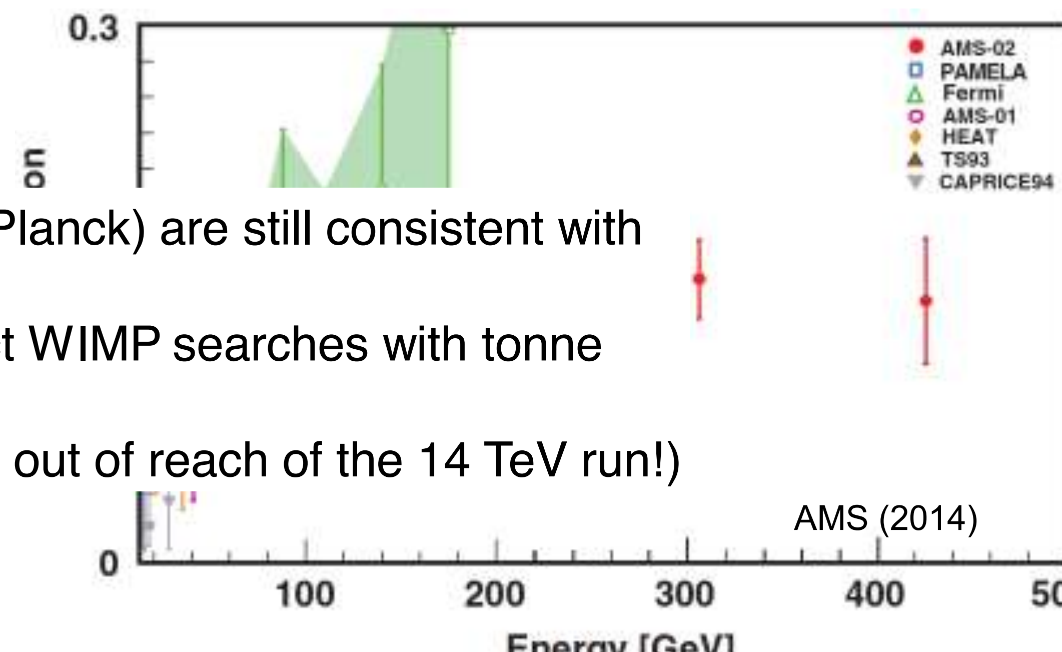
- Since 2010, sensitivity improved by ~100 (for m ~ 100 GeV)
- Further improvements by 2-3 orders of magnitude expected by a suite of experiments world-wide



- 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!)

ICHEP 2016 -- I. Shipsey

Beyond neutrino floor directional detection needed



Search for New Physics

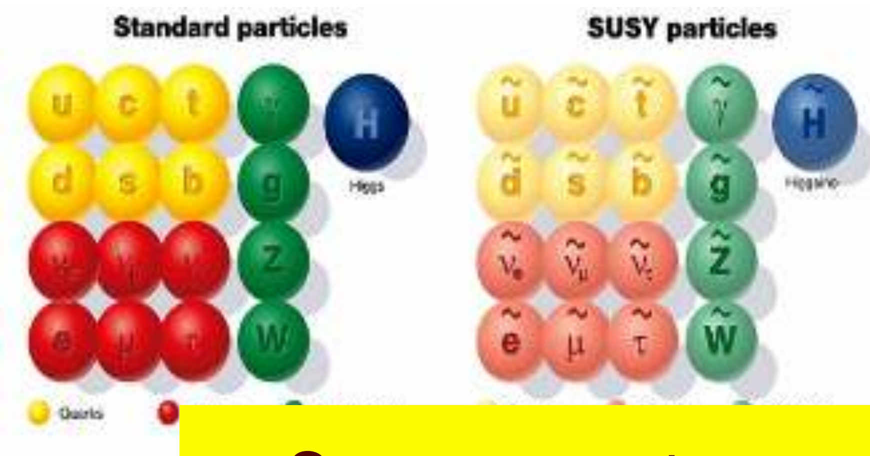
SUSY

Supersymmetry - Target # 3

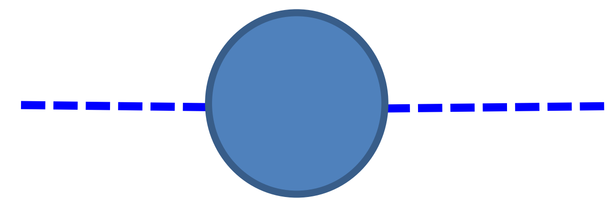
SUSY has been the prime candidate for BSM physics near the TeV scale.

Kiwoon Choi

(ICHEP 2016, Chicago)

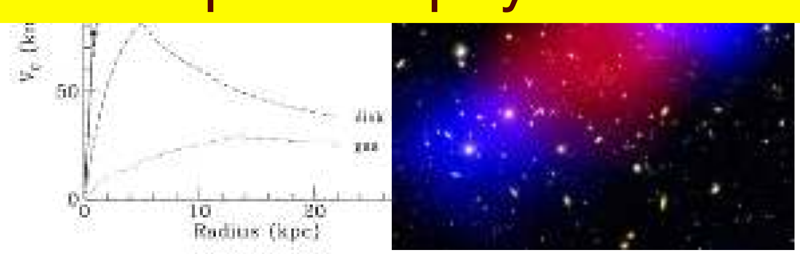


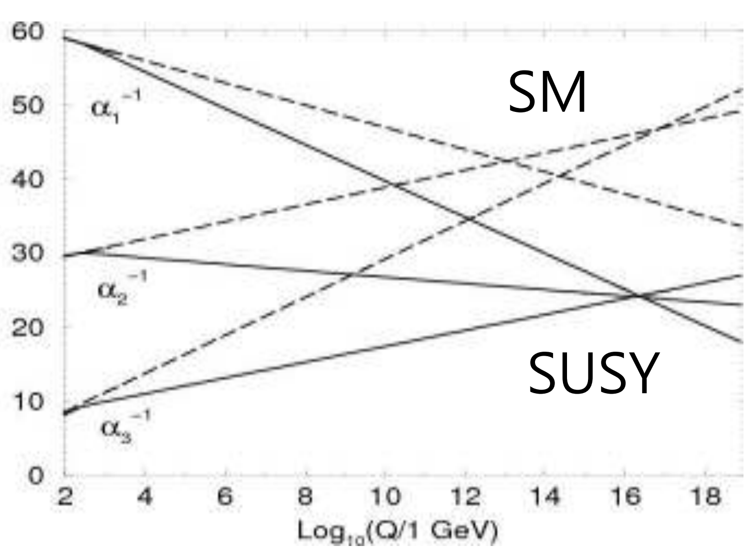
Hierarchy problem



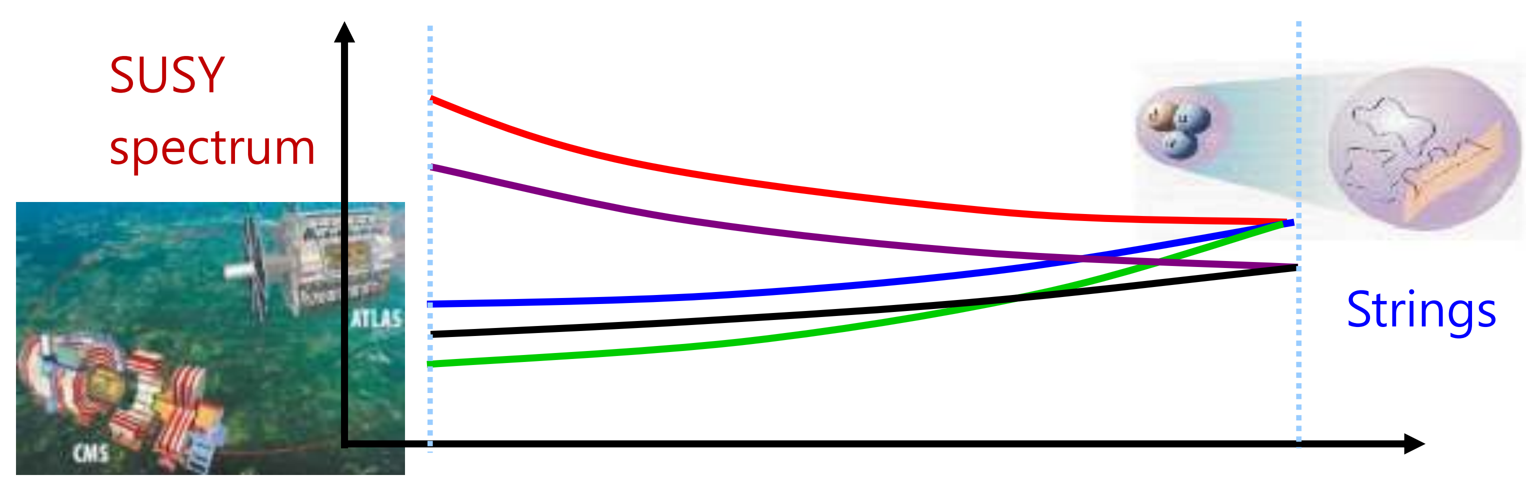
$$\delta m_H^2 \sim M_{\rm Planck}^2 \Rightarrow m_{\rm SUSY}^2$$

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



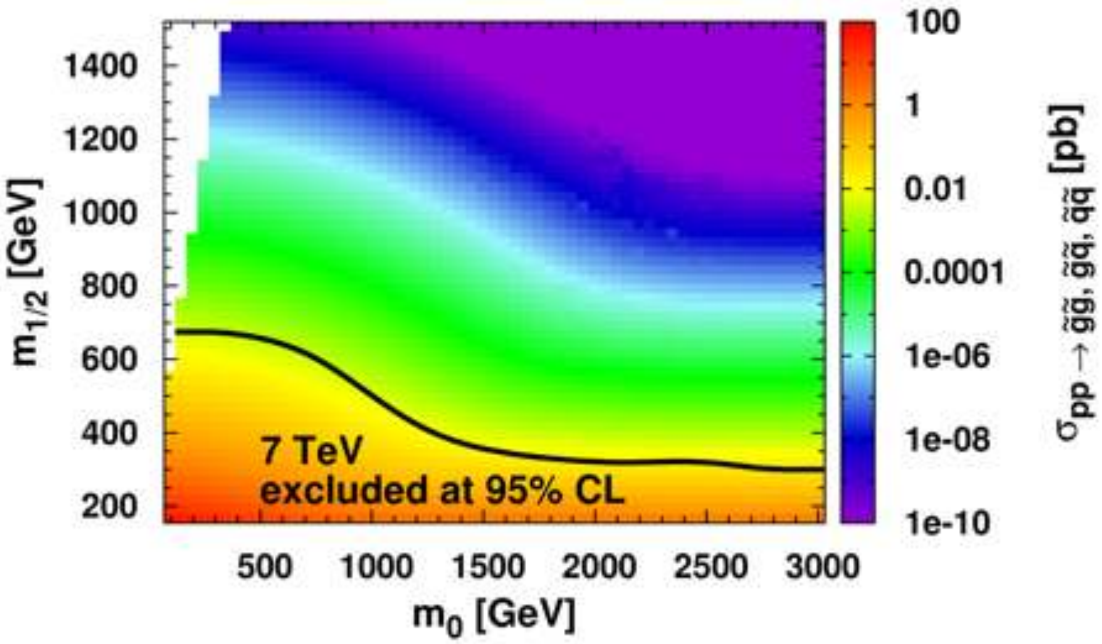


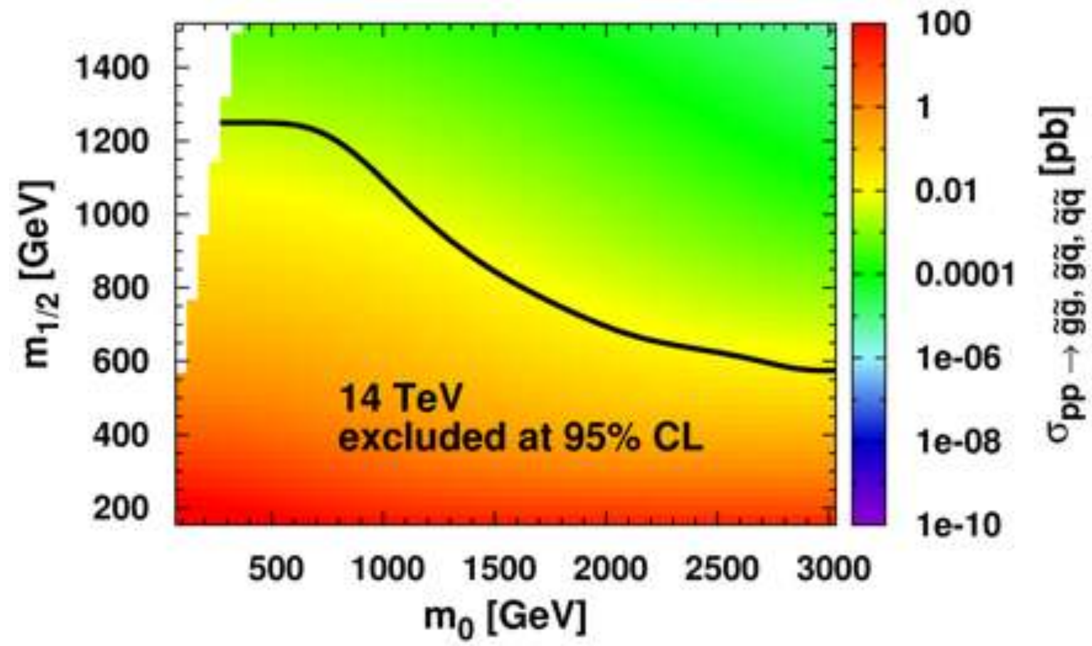
Gauge coupling unification



What is the LHC Reach?

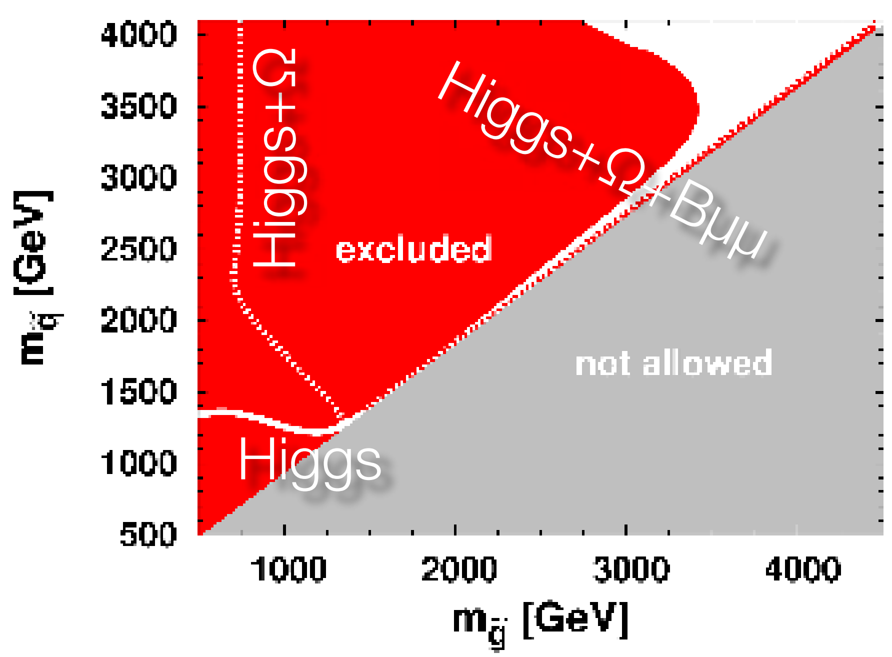
Universal scenario



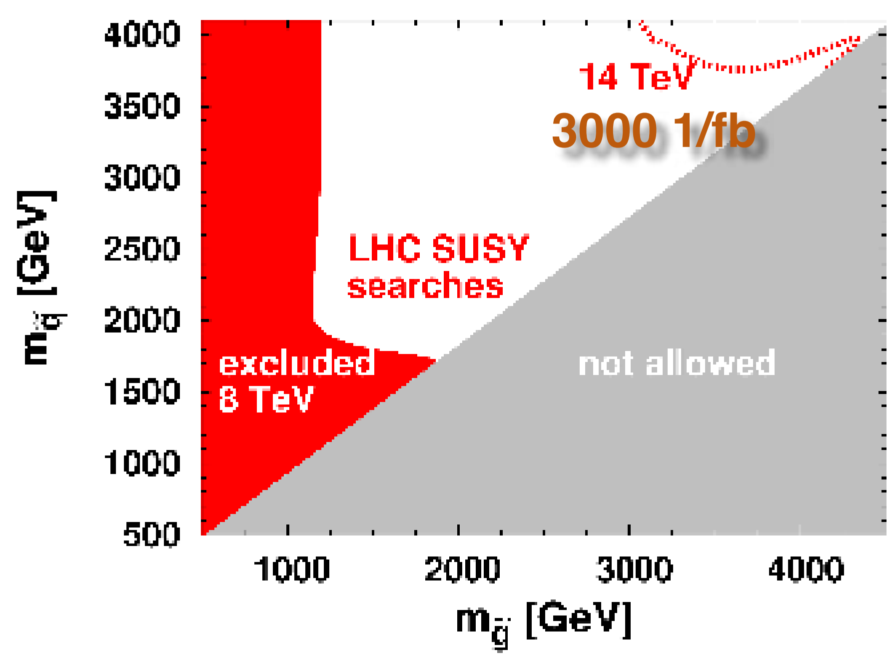


Masses of superpartners

CMSSM



NMSSM

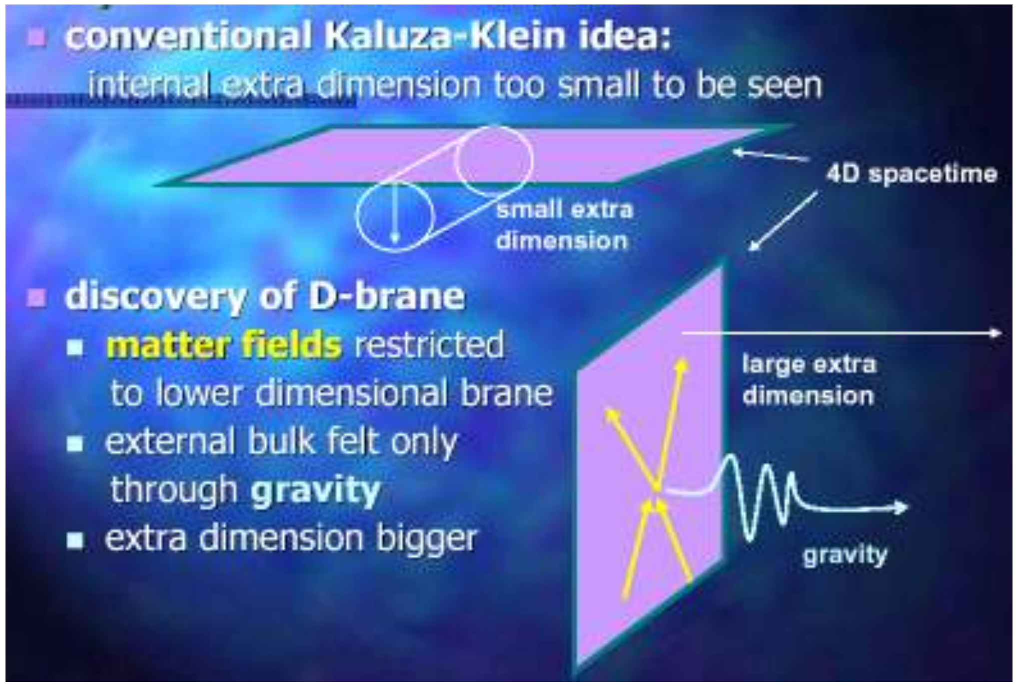


LHC Run2

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

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

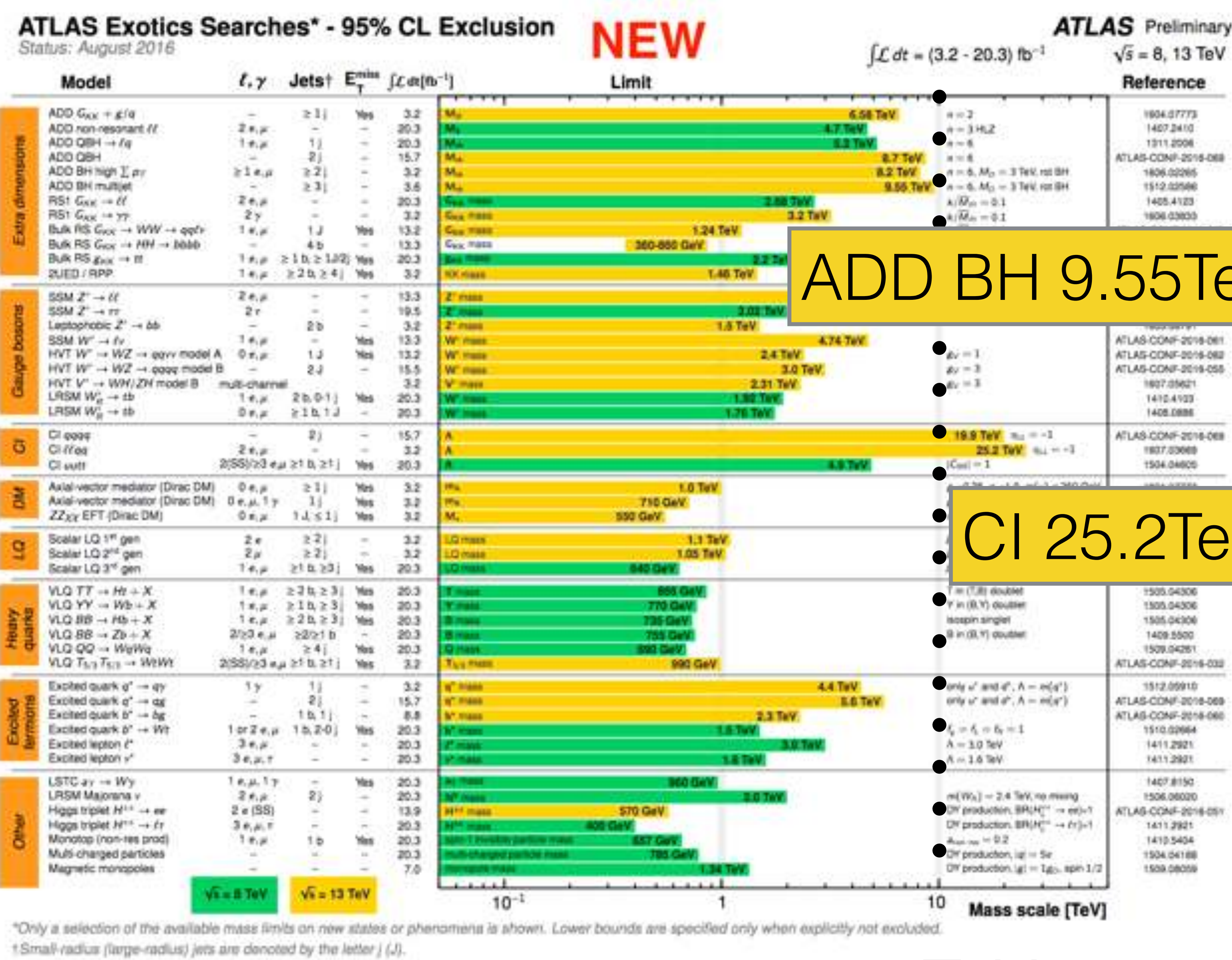
Exotics

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

Drawback: No real motivation -> Unknown scale

Resonance search summary

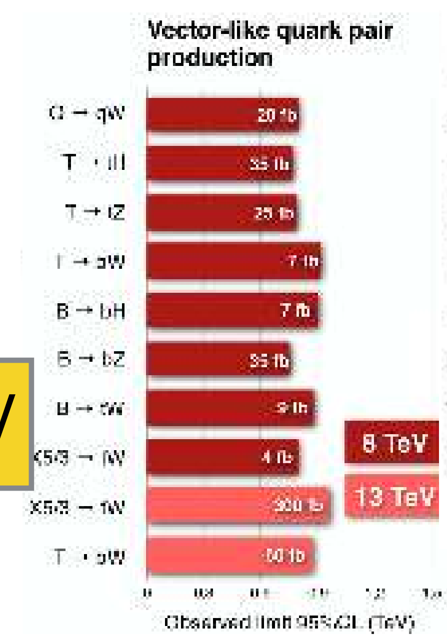
- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2

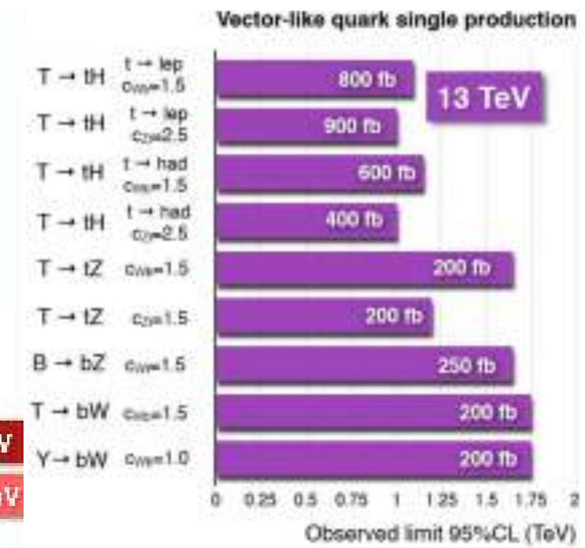


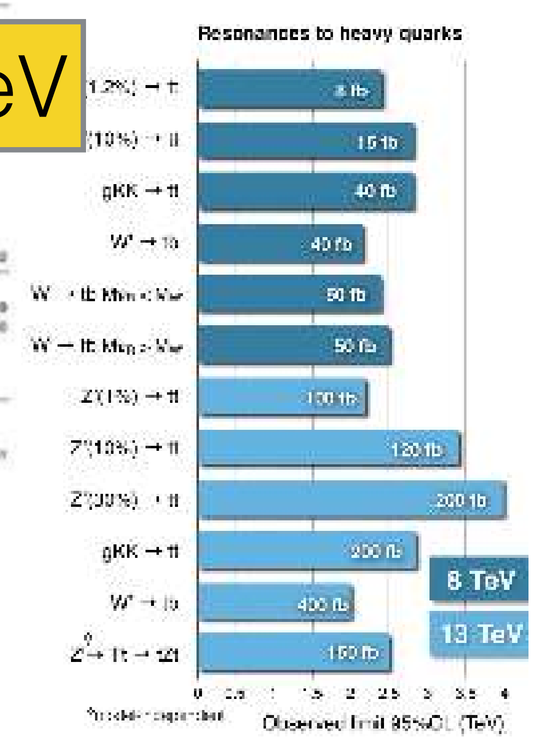
ADD BH 9.55TeV

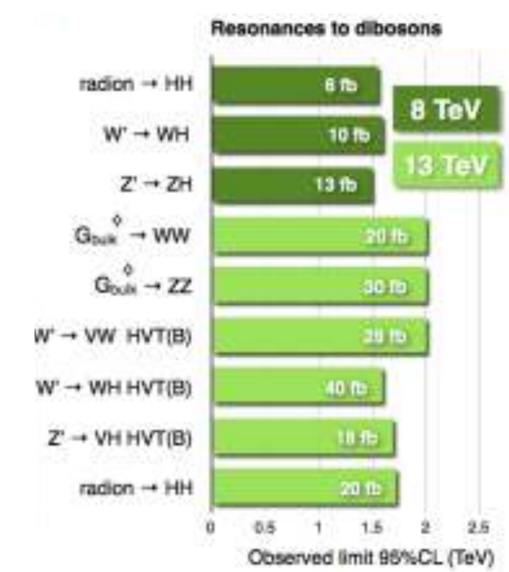
CI 25.2TeV

10TeV



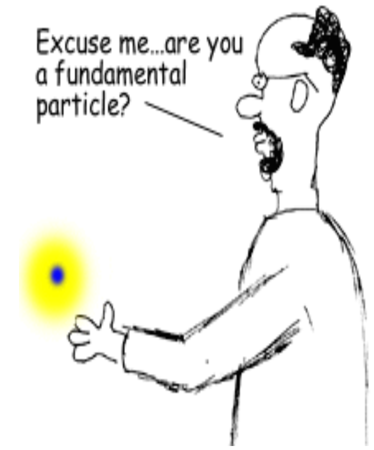






Search for New Physics

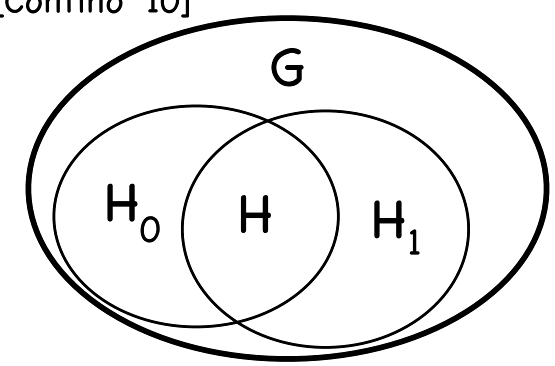
Compositeness



New level of fundamental particles

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 development ... crucially depends on LHC outcome
- Complim... arches for dark matter and insights in neutrino physics are ... extreme importance
- The areas that were left behind come to the front: confinement, exotic hadrons, dense hadron matter

I bet that discoveries will come!