Open Questions in Particle Physics and its Interface with Cosmology

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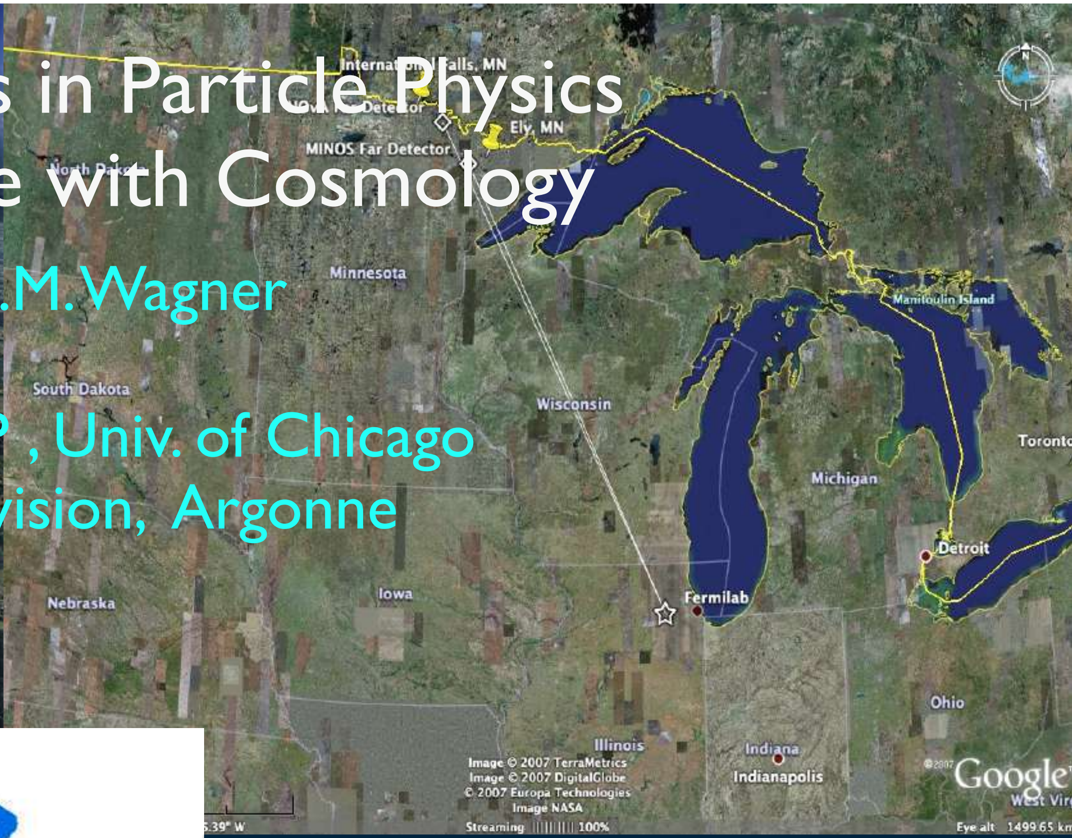
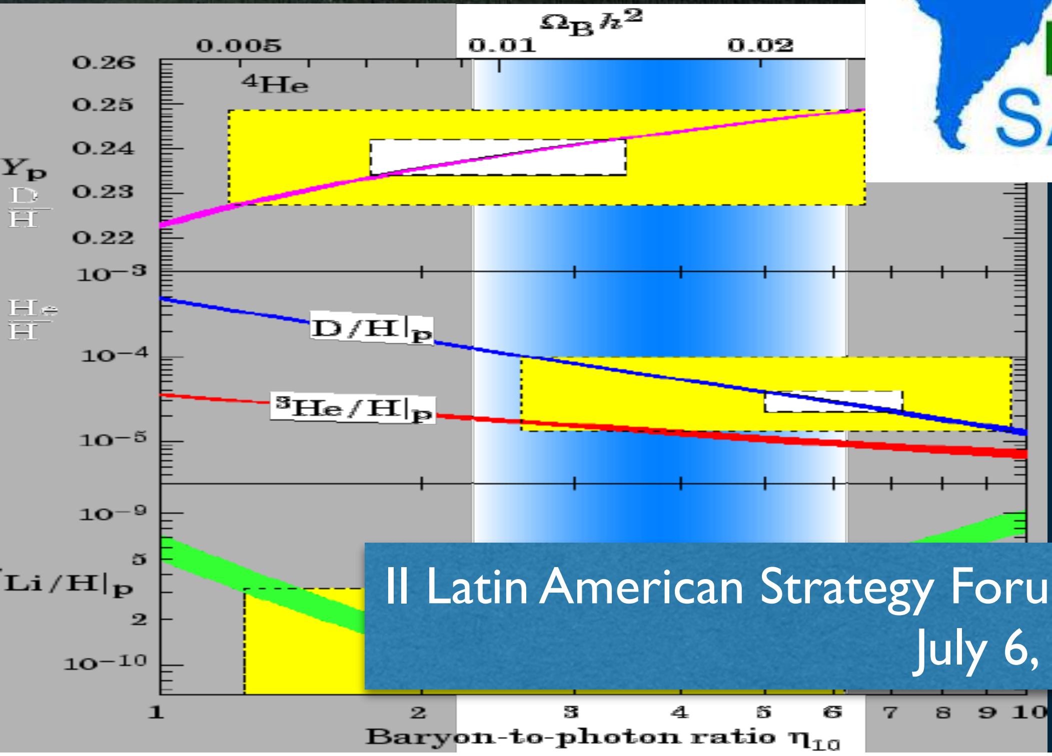
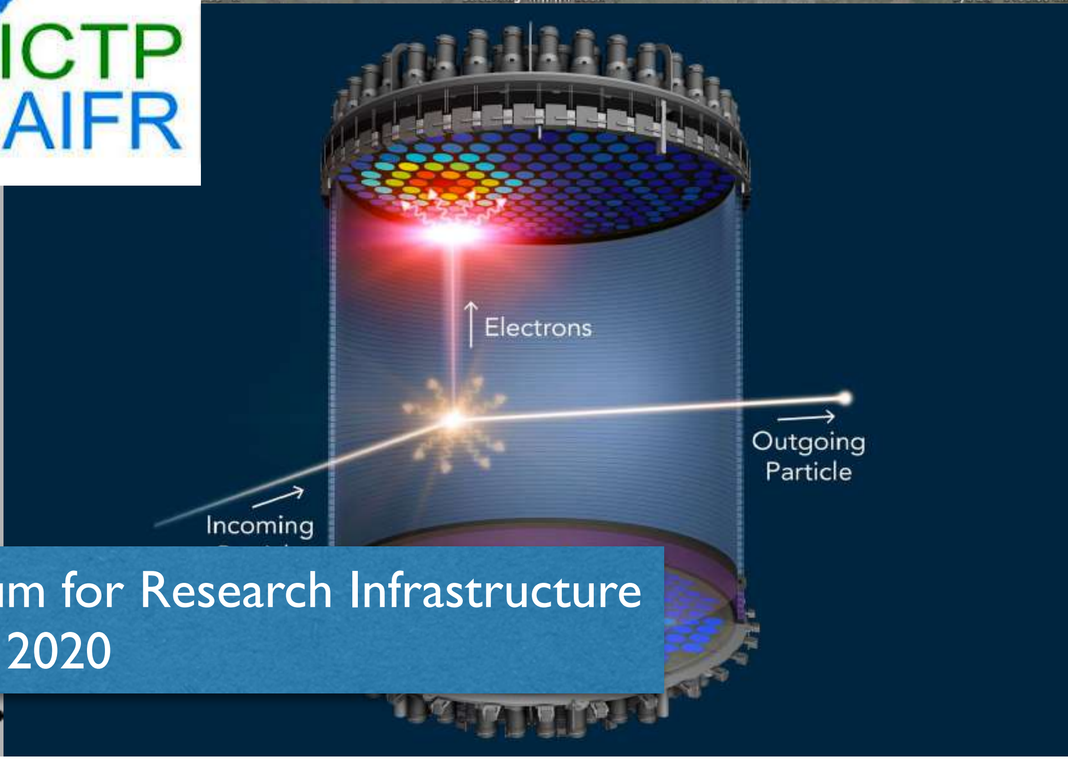


ICTP SAIFR





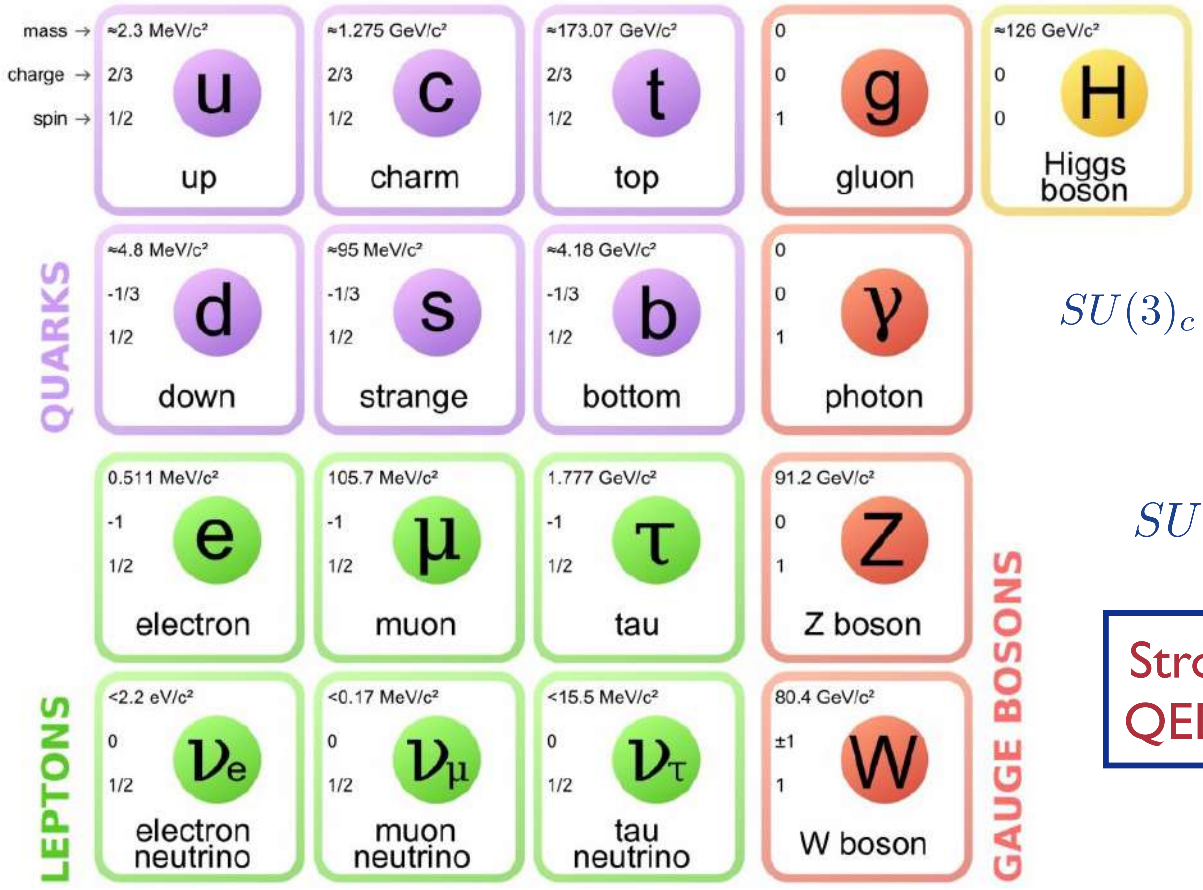
II Latin American Strategy Forum for Research Infrastructure
July 6, 2020

The Standard Model

Is an extremely successful Theory that describes interactions between the known elementary particles.

3 generations
of fermions (mattter)

Gauge and Higgs
Fields



$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\Big\downarrow \qquad < H >= \frac{v}{\sqrt{2}}$$

$$SU(3)_c \times U(1)_{\rm em}$$

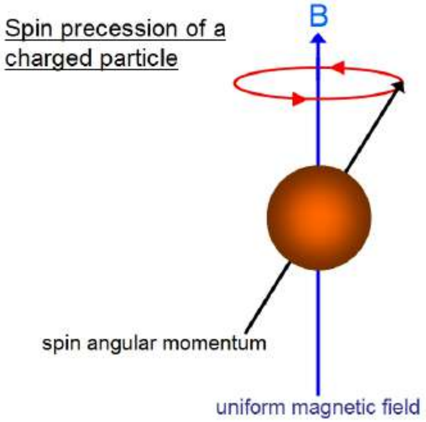
Strong, Weak and QED Interactions

Feynman, Schwinger, Tomonaga, 1965 Nobel Prize

Test of QED : Precession and Cyclotron frequencies

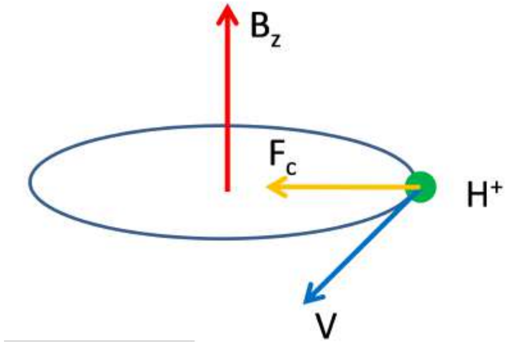
- The precession frequency of the lepton spin in a magnetic field is controlled by the so-called g-factor ($g \simeq 2$)

$$\vec{\omega}_S = -\frac{qg\vec{B}}{2m} - \frac{q\vec{B}}{\gamma m}(1-\gamma)$$



- That can be compared with the cyclotron frequency

$$\vec{\omega}_C = -\frac{q\vec{B}}{m\gamma}.$$



$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

- Hence,

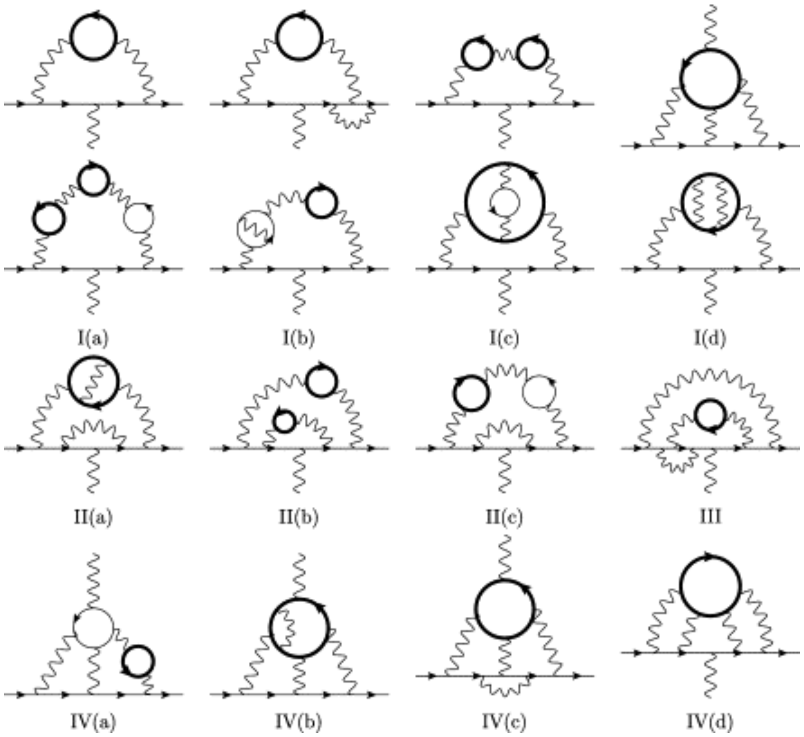
$$\omega_a = \omega_C - \omega_s = \left(\frac{g-2}{2}\right)\frac{qB}{m}$$

- Most measurements of g-2 are based on clever ways of measuring these frequency difference in a uniform magnetic field.

Schwinger realized that this g-factor is modified by quantum corrections

$$a_e = \frac{g_e - 2}{2} = \frac{\alpha}{2\pi} + \ldots$$ (Anomalous magnetic moment)

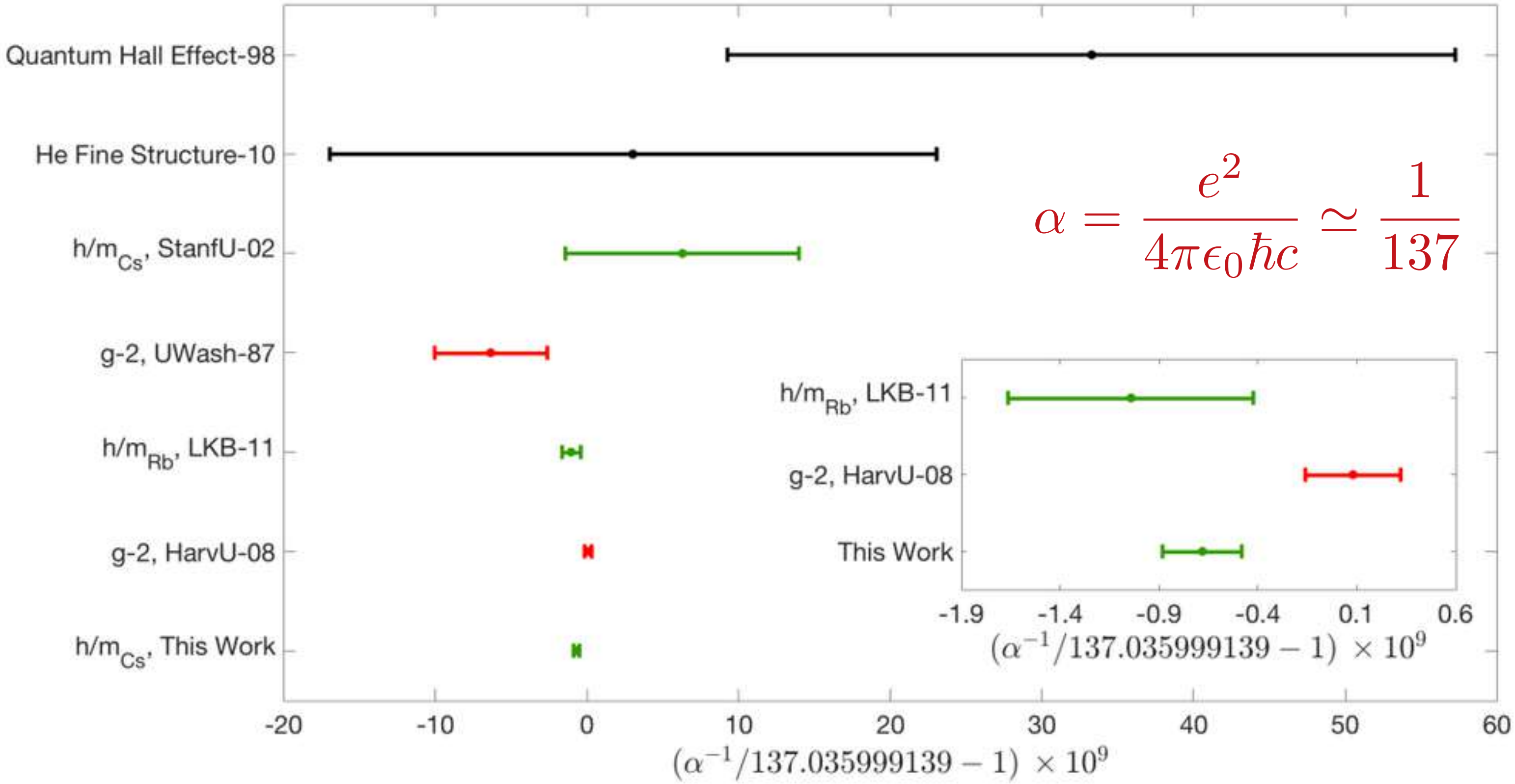
Aoyama, Hayakawa, Kinoshita'12



Today, the electromagnetic corrections to g-2 of the electron are known up to five loops, and the agreement between theory and experiments is one of the greatest triumphs of science and of the SM

Electron g-2 factor

Two precise determinations of the inverse of the fine structure constant α seem to agree at a spectacular precision, one of them is coming from g-2. Difference of order a few 10^{-10}



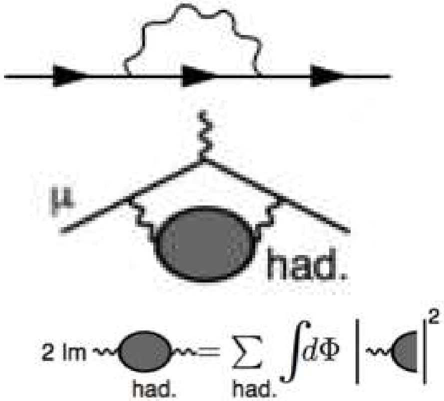
$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \simeq \frac{1}{137}$$

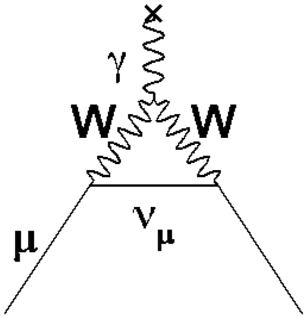
This could indicate new physics, to fix the electron g-2

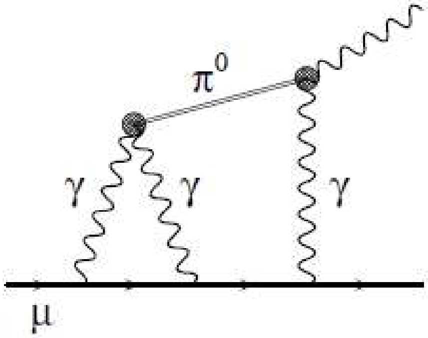
New (pseudo) scalars, with masses of the order of a few 10s of MeV and (small) loop induced couplings to the electron

Marciano et al'18
Liu et al'19

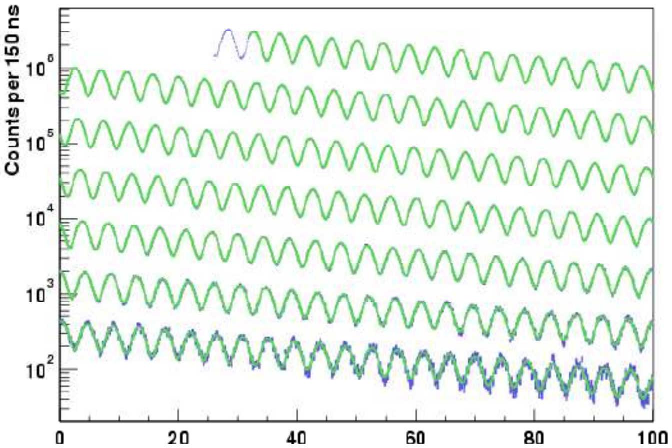
Muon g-2 factor







Brookhaven result



$$\frac{(g-2)}{2}(BNL) = 0.00116592089(63)$$

hep-ph/0602035

$$\frac{(g-2)}{2}(SM) = 0.00116591802(49)$$

Davier, Hocker, Zhang, arXiv:1706.09436
UKQCD coll, arXiv:18001.07224

$$\Delta a_{\mu} = (2.74 \pm 0.73) \times 10^{-9}$$

Discrepancy between Theory and Experiment at the 3.5 σ level

Open Question : Is this a hint of New Physics ?

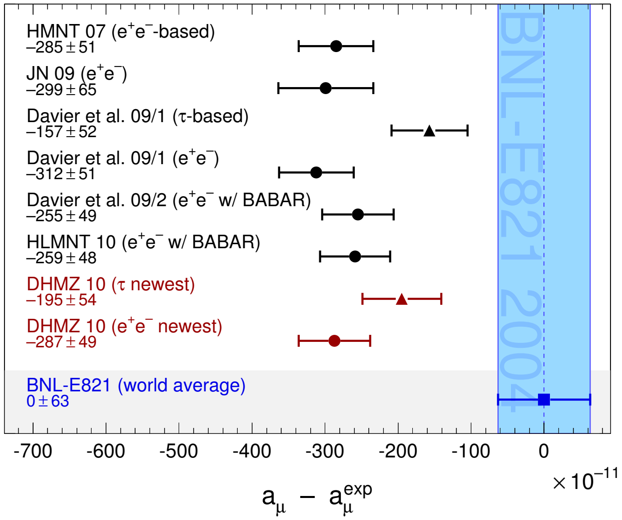
New Physics : Supersymmetry
Muon Anomalous Magnetic Moment

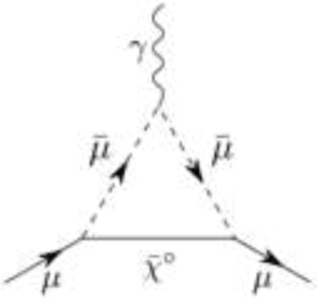
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

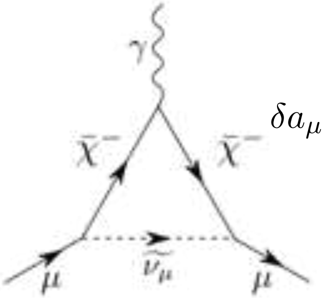
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{th} = 279\ (76) \times 10^{-11}$$

3.7 σ Discrepancy

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry







$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2}\frac{m_\mu^2}{\widetilde{m}^2}\mathrm{Sgn}(\mu M_2)\tan\beta \simeq 130\times 10^{-11}\left(\frac{100\ \mathrm{GeV}}{\widetilde{m}}\right)^2 \mathrm{Sgn}(\mu M_2)\tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

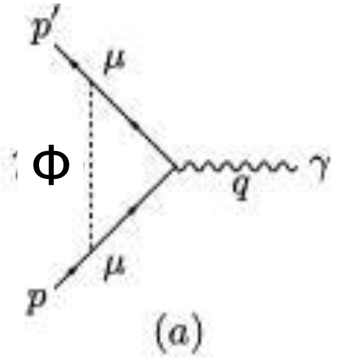
For $\tan\beta \simeq 10\ (50)$, values of $\tilde{m} \simeq 230\ (510)$ GeV would be preferred.

If Winos are heavy, one would need larger values of tanβ to explain the current anomaly.

New physics ? Too many possibilities.

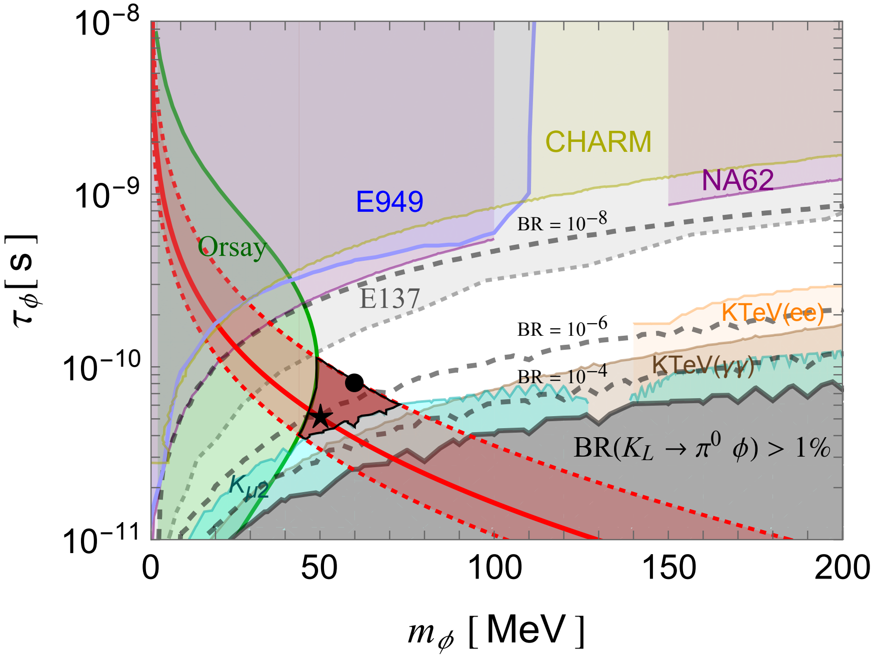
Marciano and Czarnecki, hep-ph/ 0102122

In a recent work, we tried to address the g-2 discrepancy, as well as to explain some strange events seen at the KOTO experiment with a single new scalar



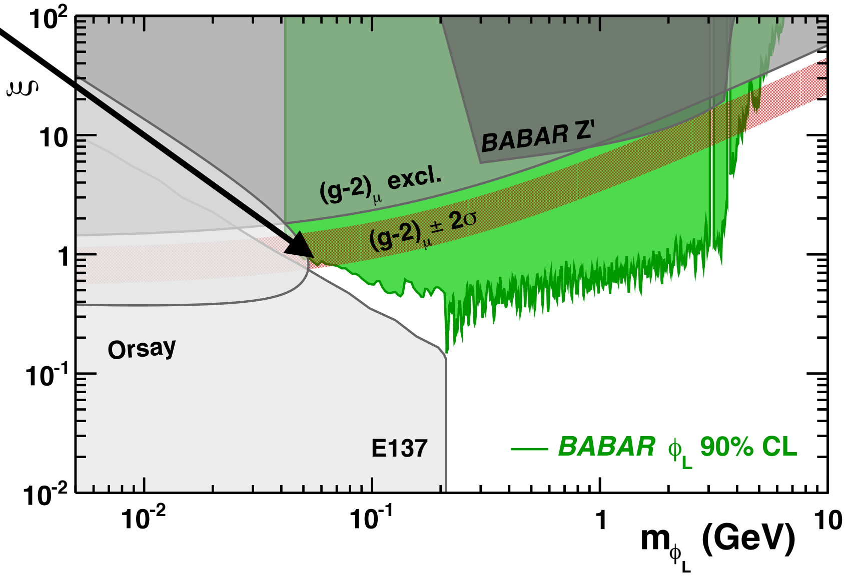
$$K^0 \to \pi^0\Phi \to \pi^0 e^+ e^-$$

McGinnis, Liu, Wang, C.W., 2001.06522



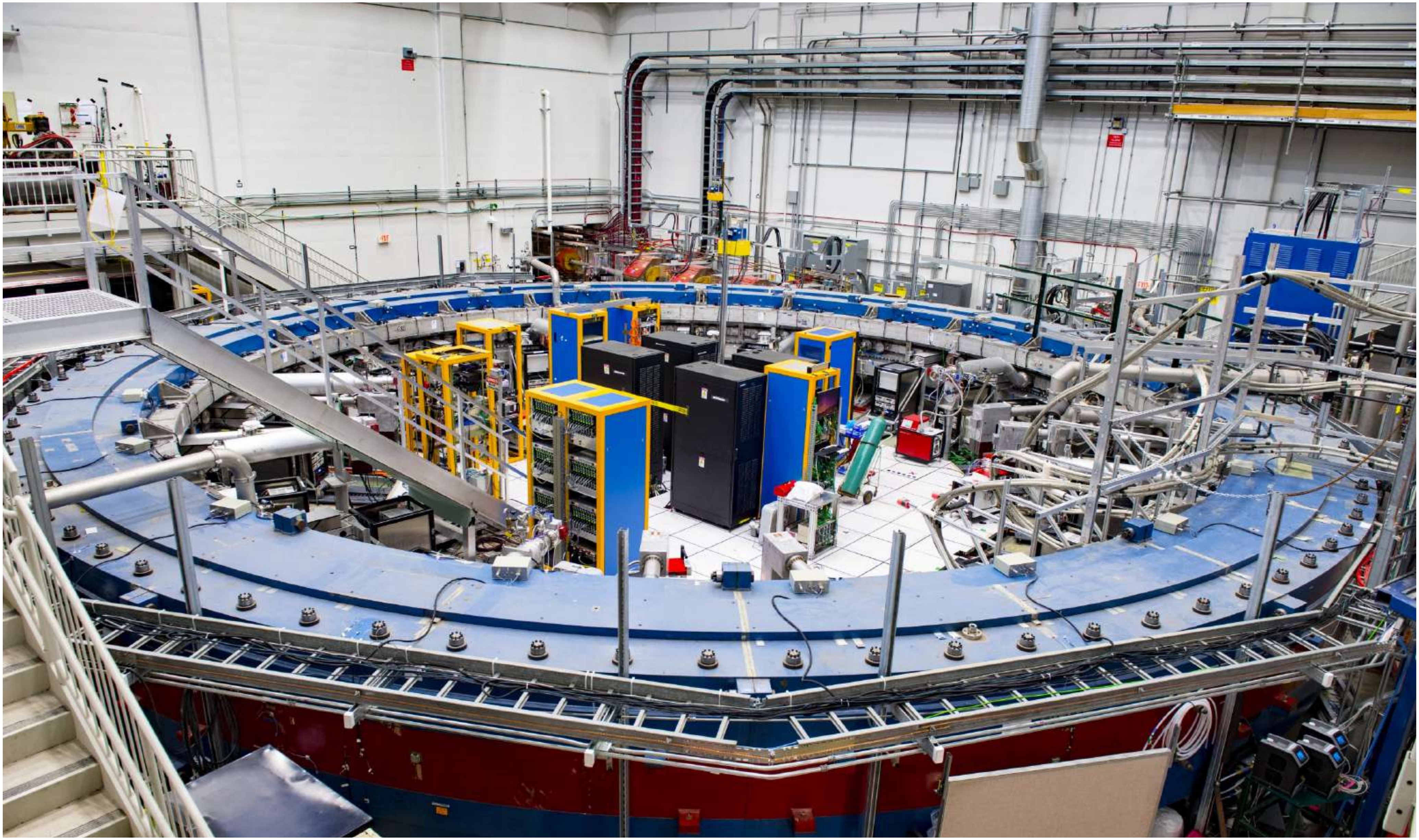
Very recently, BABAR put constraints on such scalars

2005.01885



New Experiment, Belle II, will settle this question

Brookhaven g-2 Results will be tested by the g-2 Experiment at Fermilab : To report results soon



Fritzsch, Gell-Mann, Leutwyler’73

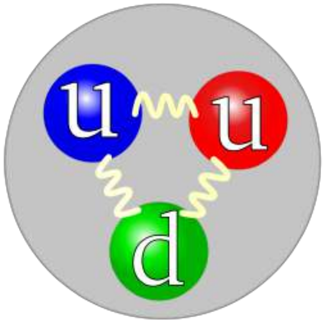
Strong Interactions Tested Perturbatively and Non-Perturbatively

$SU(3)_C$

Dynamical Mass Generation

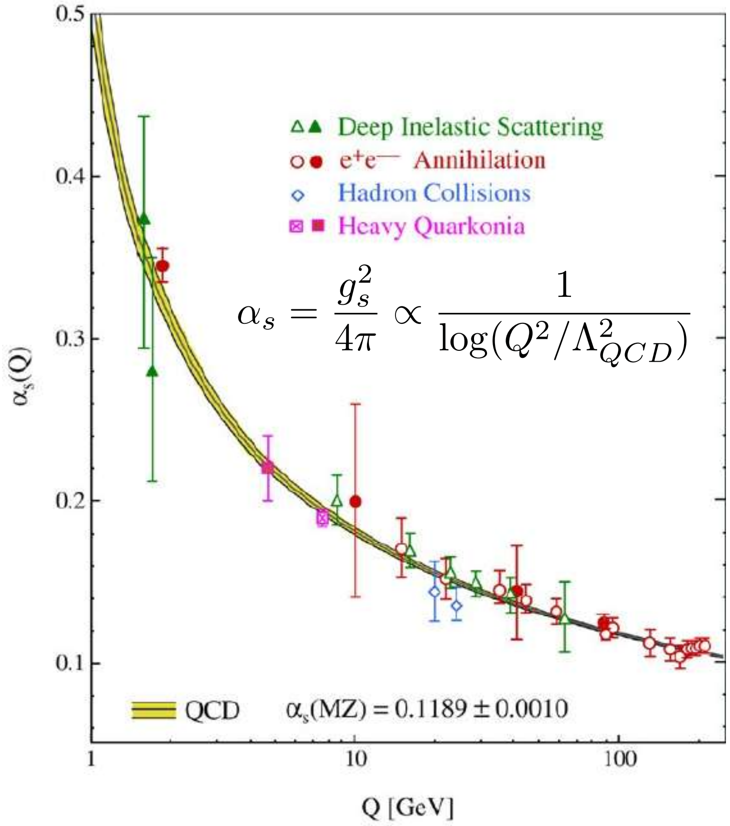
Confinement

Nambu, Nobel Prize 2008

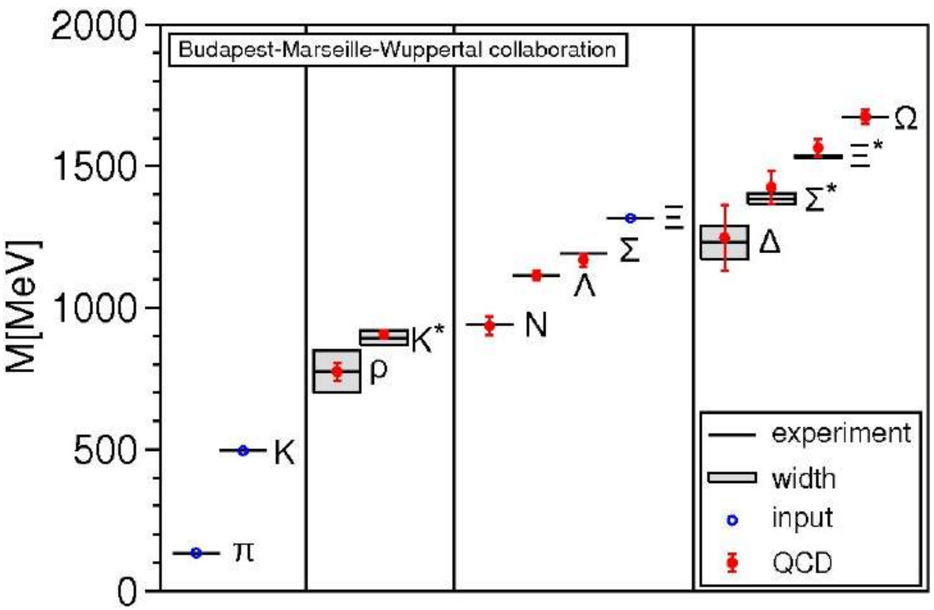


- Protons and neutrons are composite of quarks interacting strongly via the interchange of gluons : QCD

- These QCD interactions become strong at scales of about 500 MeV, what sets the characteristic scale for baryon masses



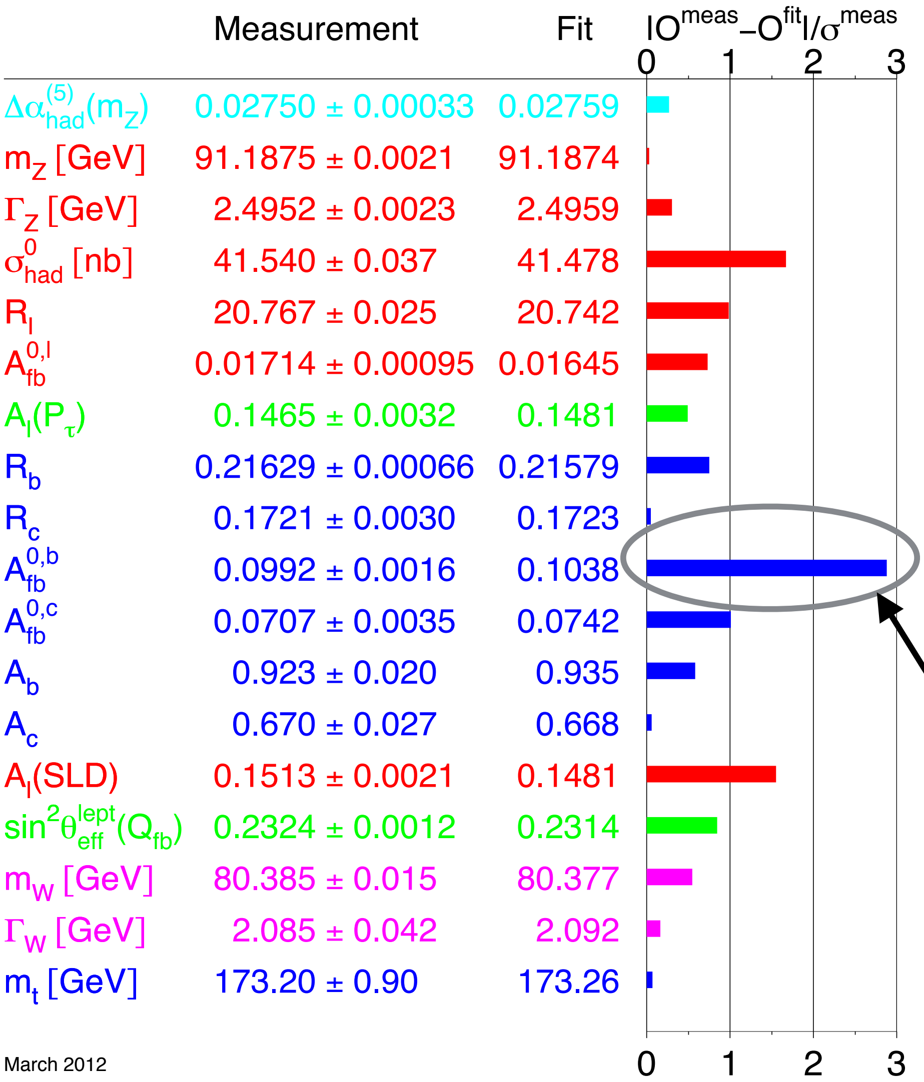
$$\alpha_s = \frac{g_s^2}{4\pi} \propto \frac{1}{\log(Q^2/\Lambda_{QCD}^2)}$$



Lattice simulations
(Path Integral Simulation of QCD)

Test of Electro-Weak Interactions : Precision Electroweak Measurements

$$SU(2)_L \times U(1)_Y$$



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

Processes measured at electron positron collisions with a center of mass close to the Z-mass.

Agreement between theory and experiment at the 10^{-3} level.

Could indicate deviation of right-handed bottom coupling to the Z with respect to the SM.

New quarks or new gauge bosons ?

Chanowitz'00, Choudhury, Tait, C.W.'01, He, Valencia'02,, Batell, Gori, Wang'12, Liu, Liu, Wang, C.W.'17

Gauge Sector well tested. What about the Higgs sector ?

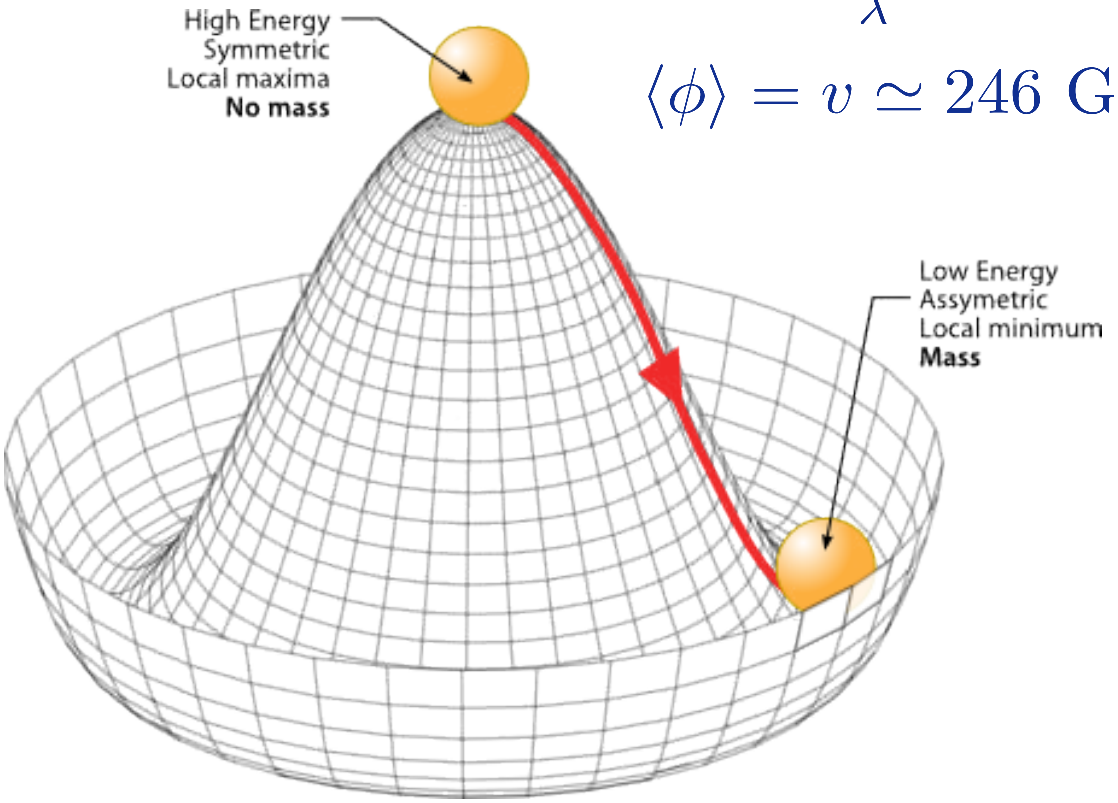
Higgs, Englert, Brout, Kibble, Guralnik, Hagen'64

Higgs vacuum : Elementary Particle Masses

$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4, \qquad m^2 < 0$$

$$v^2 = -\frac{m^2}{\lambda}$$

$$\langle\phi\rangle = v \simeq 246 \text{ GeV}$$



Particle acquire mass through interactions with Φ.

Couplings proportional to the ratio of mass to v

$$m_f = h_f \frac{v}{\sqrt{2}}$$

$$m_W = g_2 \frac{v}{2}$$

$$m_Z = \sqrt{g_2^2 + g_1^2}\,\frac{v}{2}$$

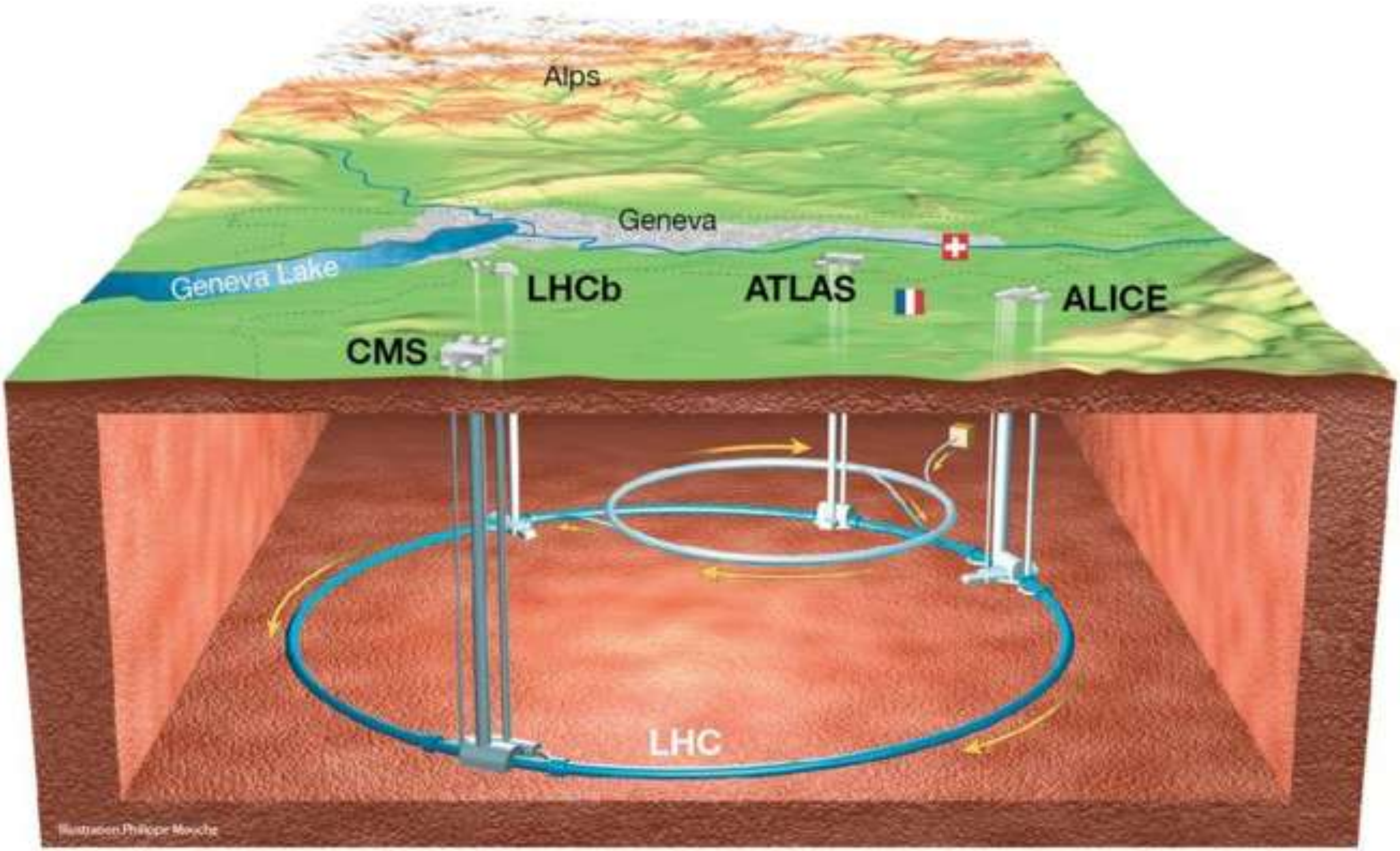
$$m_\gamma = m_g = 0$$

Physical state h associated with fluctuations of ϕ, the radial mode of the Higgs field.

$$m_h^2 = \lambda v^2$$

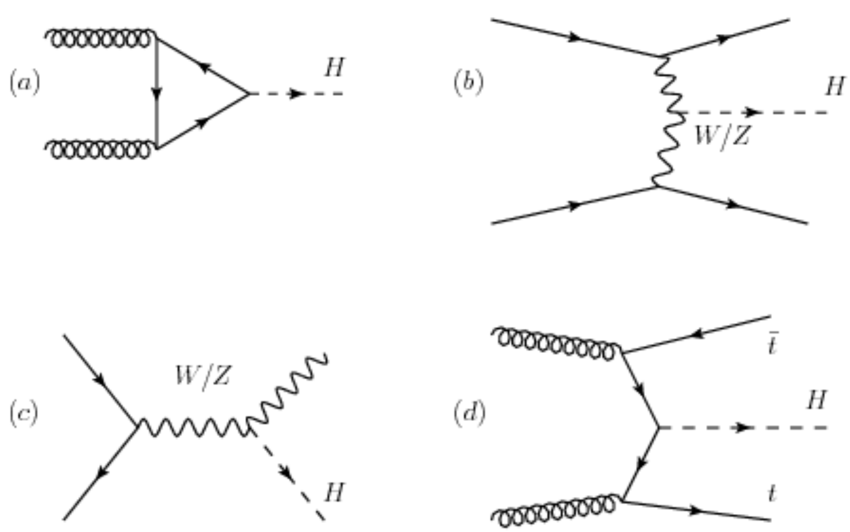
Testing Higgs' hypothesis : Looking for the Higgs boson

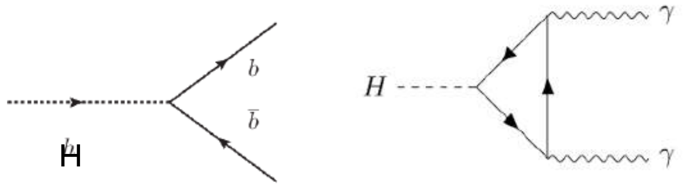
The Large Hadron (proton against proton) Collider (LHC)

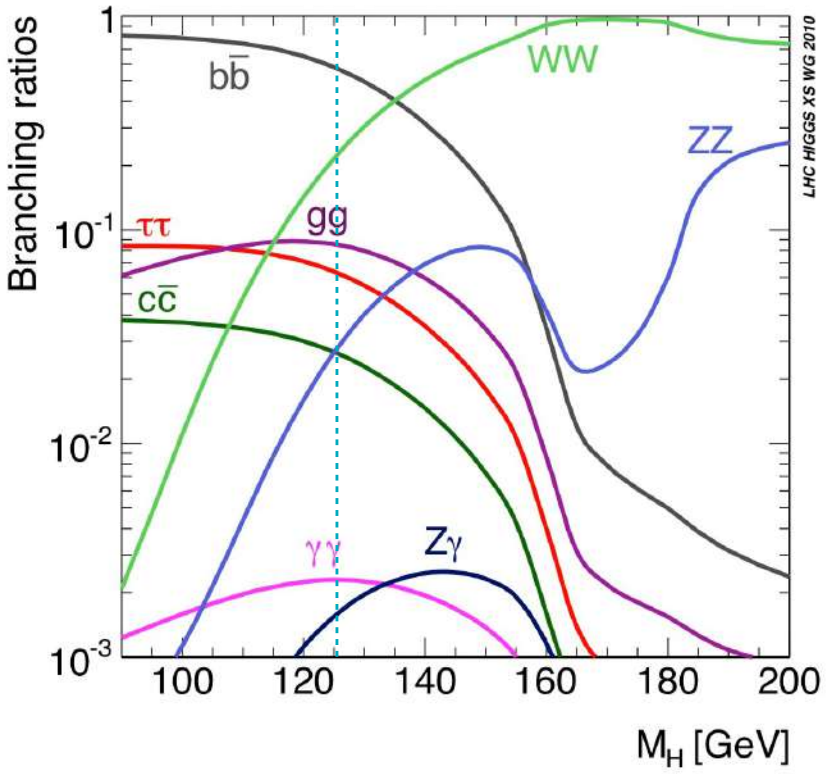


We collide two protons (quarks and gluons) at high energies :

LHC Higgs Production Channels and Decay Branching Ratios







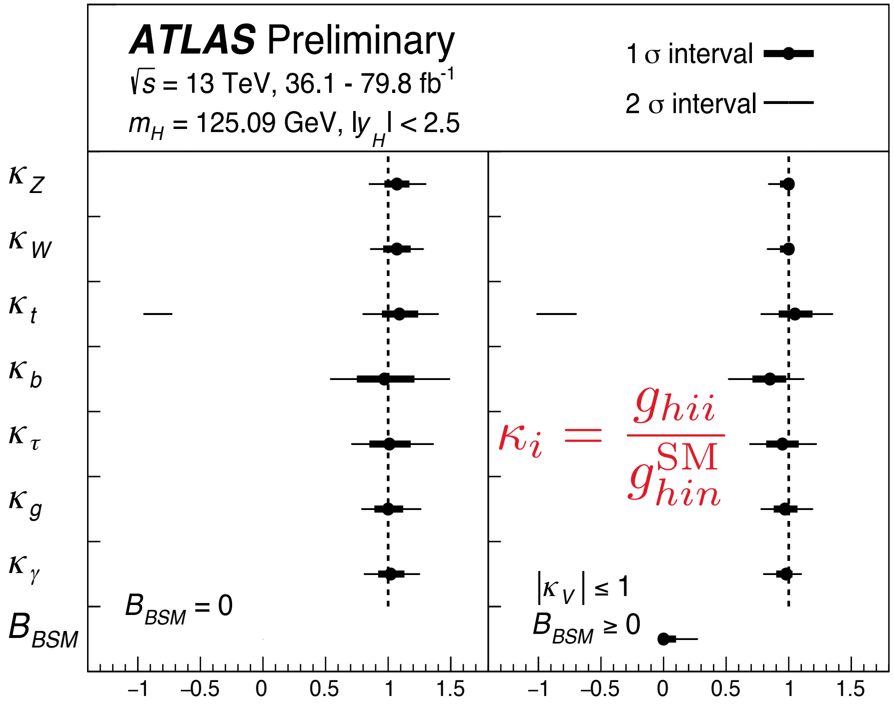
A Higgs with a mass of about 125 GeV allows to study many decay channels

Open Question : Is the Higgs the SM one ?

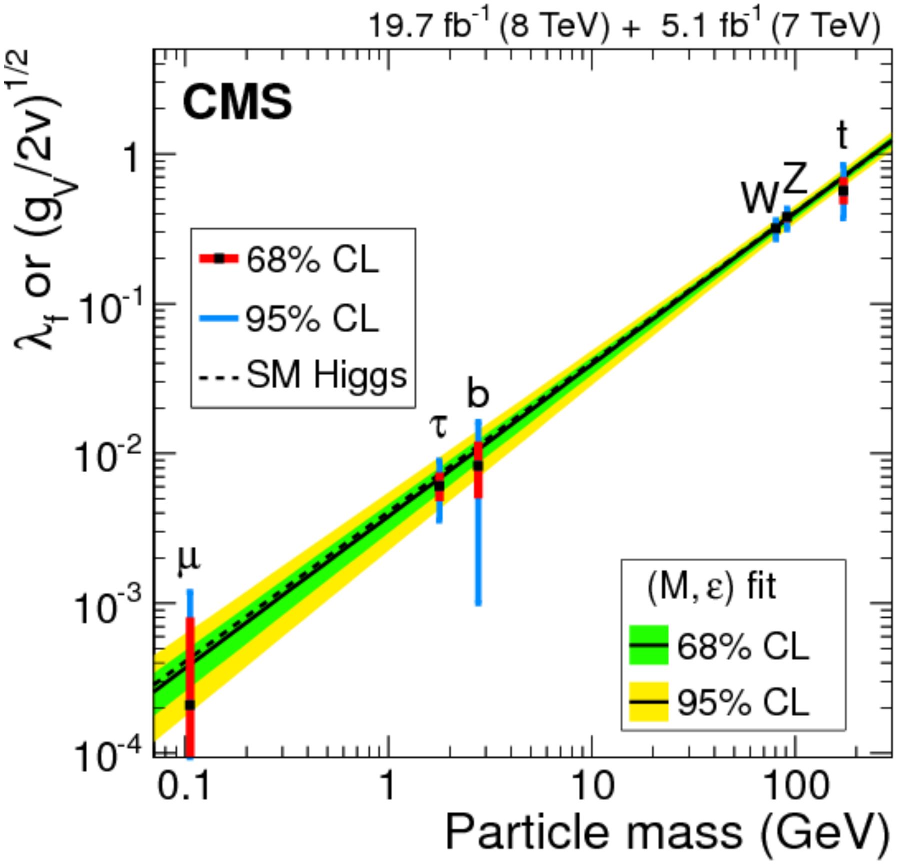
Linear correlation of masses and Higgs couplings established.
Another Standard Model triumph

Agreement at the 20 percent level :
More precision is needed.
High Luminosity LHC Program

$$g_{HPP} \propto \frac{m_P}{v}$$



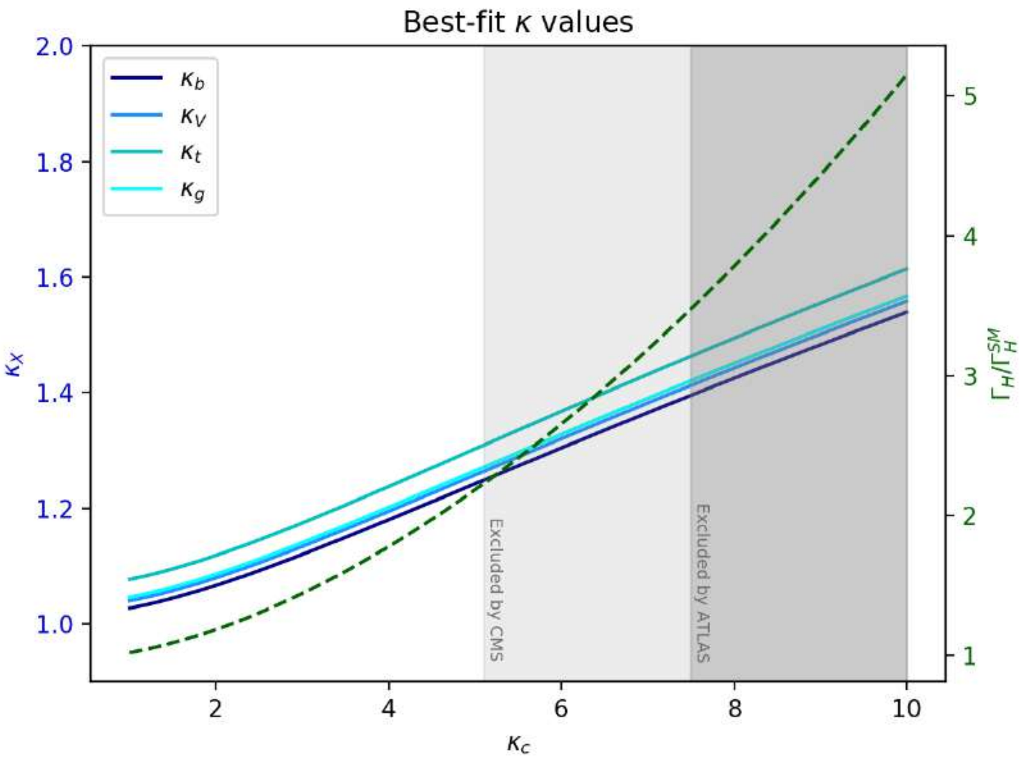
$$\kappa_i = \frac{g_{hii}}{g_{hin}^{\rm SM}}$$



What about the first two generation masses ?

Perez et al'16

What do we know of the charm quark coupling ?



Flat Direction.

It is broken by Higgs width
Nina Coyle and Viska Wei, C.W. ,
arXiv:1905.09360

$$\kappa_c < 5$$

The fit to the Higgs couplings, complemented with the analysis of charm-related Higgs production channels

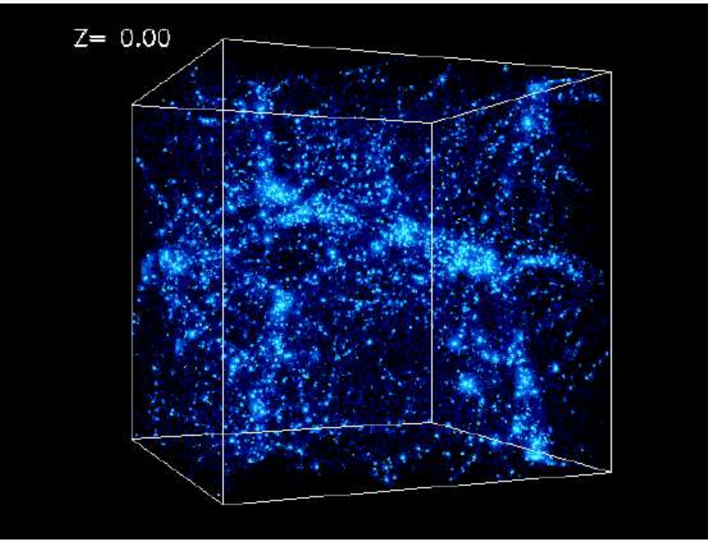
$\kappa_c < 2$ at the high luminosity LHC

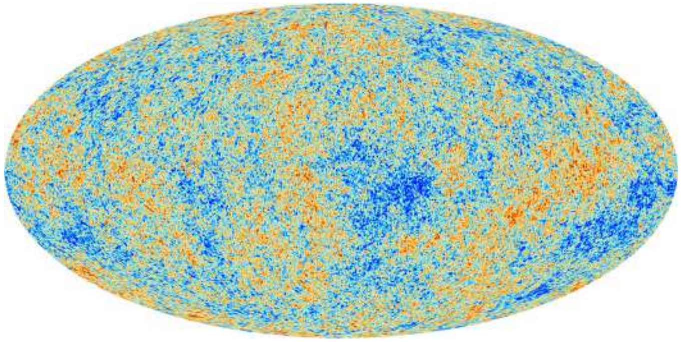
We need alternative experiments to probe these couplings.
Powerful electron-positron or muon colliders ?
Higher Energy proton proton collider ? (100 TeV)

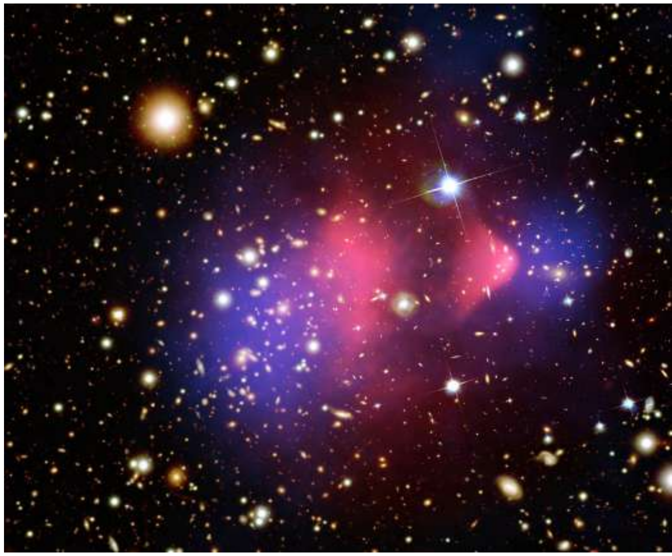

Now What?

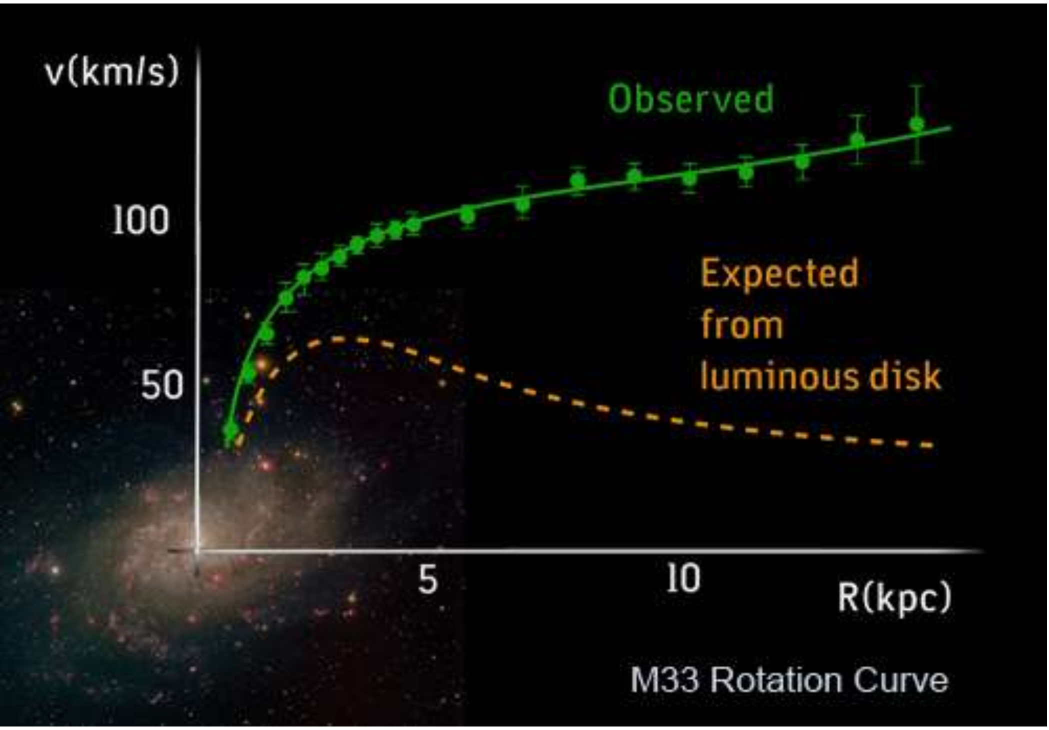
Open Question :What is the Dark Matter ?

Existence of Dark Matter Supported by overwhelming indirect evidence

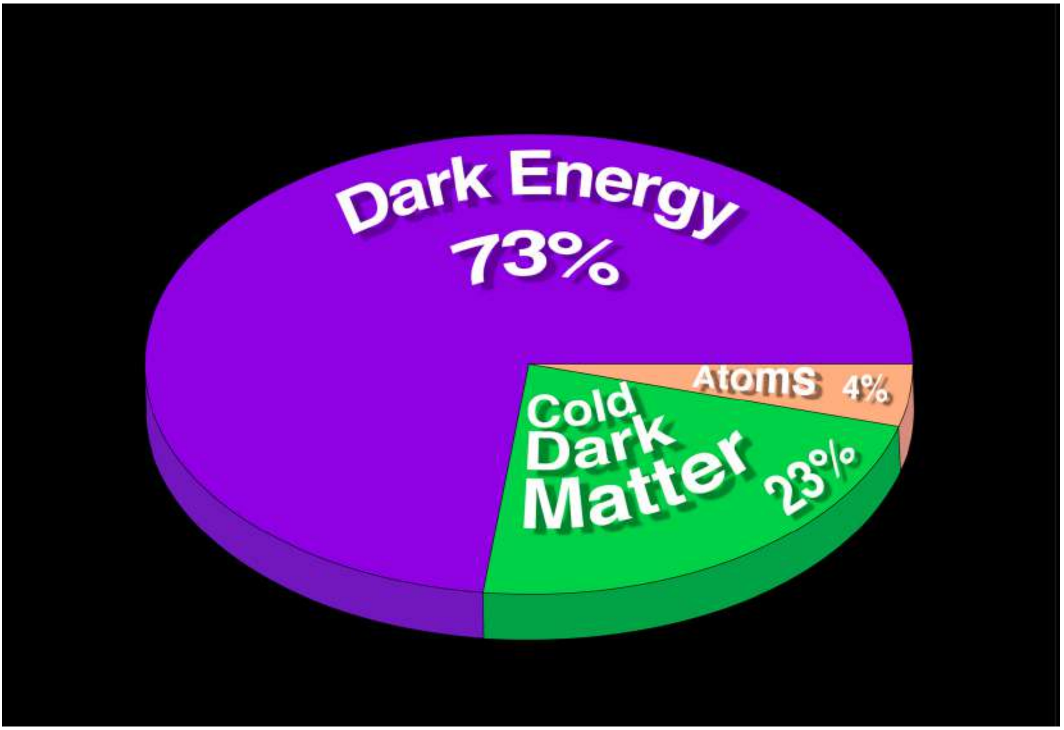








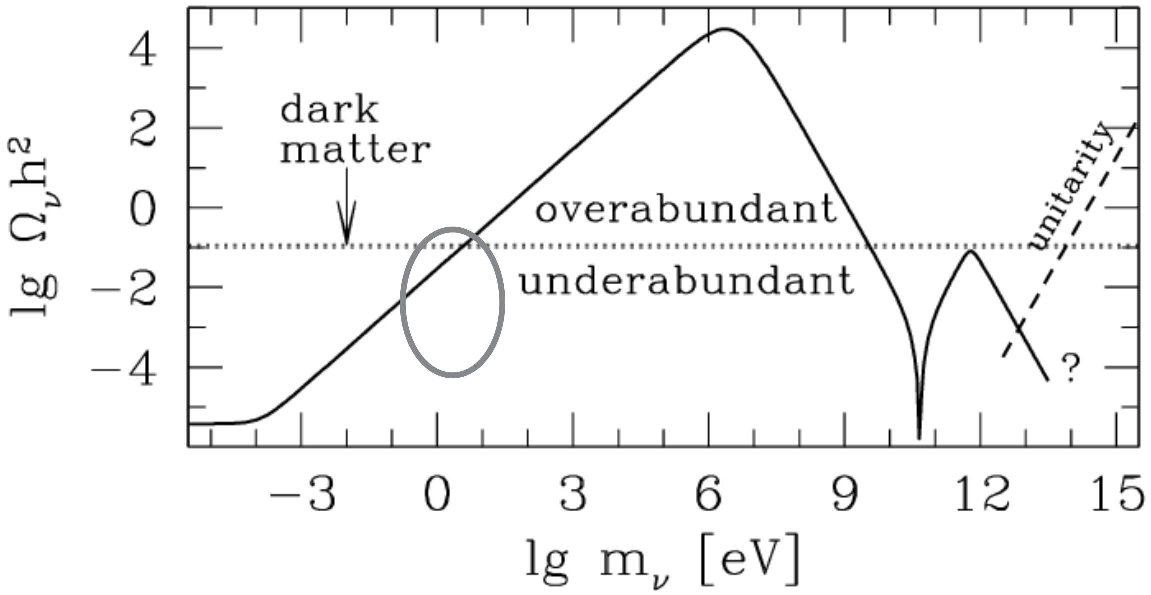
M33 Rotation Curve



Do we need a new particle, to explain DM ?

The SM has particles that are neutral, stable and weakly interacting, and are therefore DM candidates, namely the neutrinos !

Neutrinos are natural relics of the Big Bang



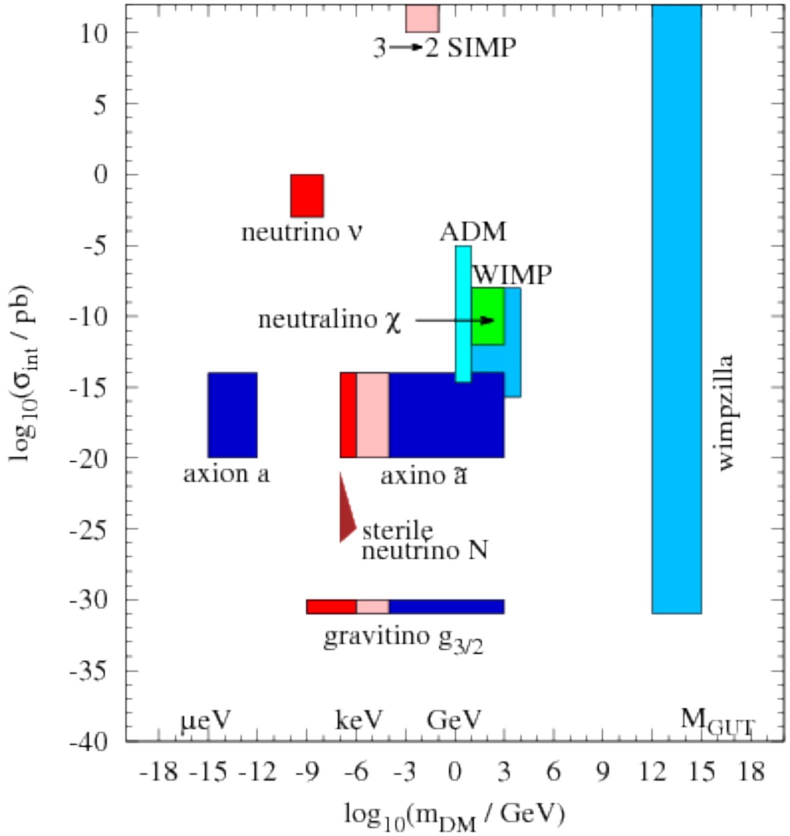
Neutrinos in the eV range have lifetimes larger than the age of the Universe and

$$\Omega h^2 \simeq \frac{\sum m_{\nu_i}}{100\ eV}$$

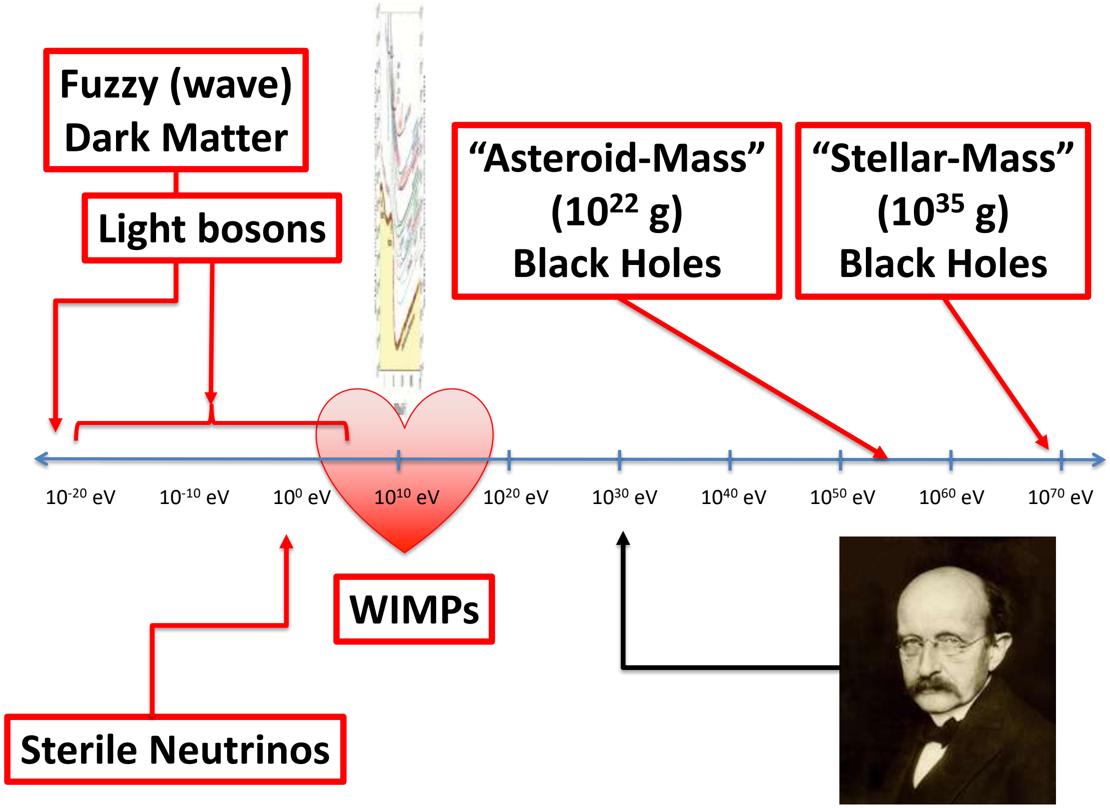
$$\left(\sum m_{\nu_i}\right)^{\exp} \geq 0.05eV$$

Today we know that neutrinos have masses below 0.2 eV and hence are only a fraction of the DM density.

Beyond the Neutrino Dark Matter scenario



Baer, Choi, Roszkowski'14



Fuzzy (wave) Dark Matter

Light bosons

"Asteroid-Mass" (10^{22} g) Black Holes

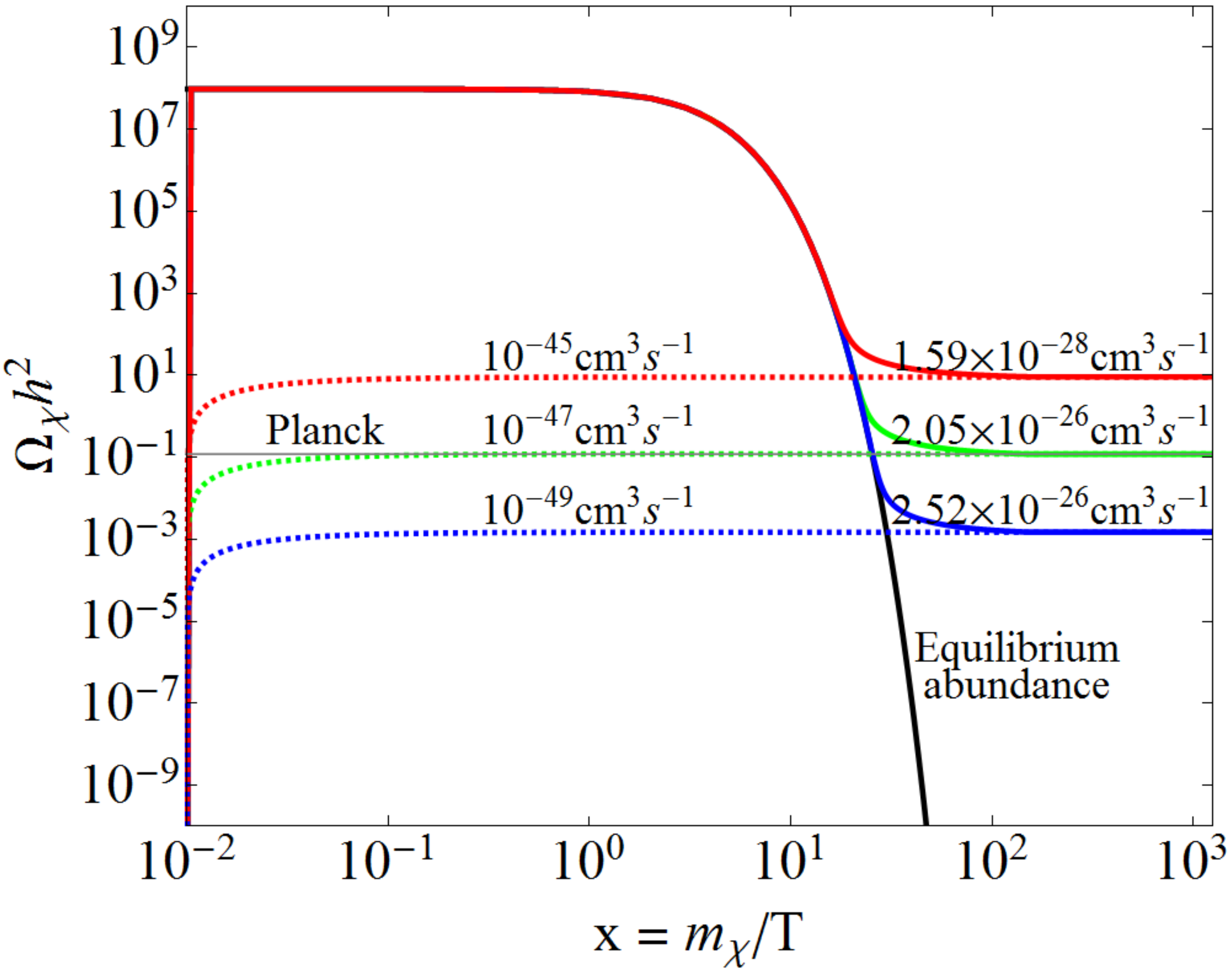
"Stellar-Mass" (10^{35} g) Black Holes

WIMPs

Sterile Neutrinos

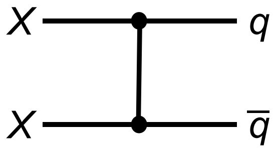
S. Profumo, Pheno Workshop, May 2020

Dark Matter as a Big Bang Relic



Kolb and Turner '90
The Early Universe

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

Weak scale size masses and couplings roughly consistent with ΩDM

WIMPS

WIMP must be neutral and stable

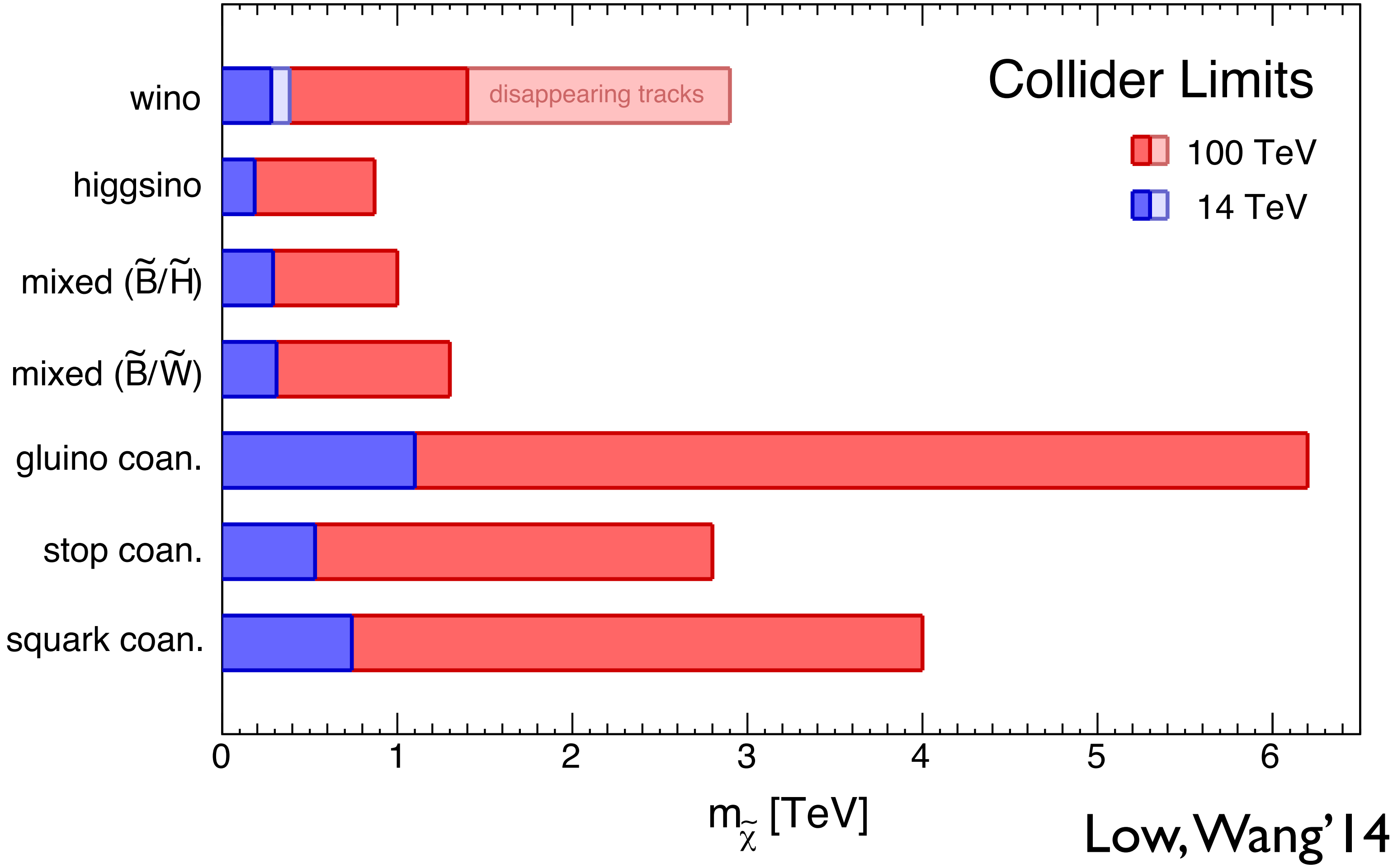
- Stability may be ensured by a discrete symmetry under which new particles are charged and SM is neutral
- Typical example is SUSY. The symmetry is R-Parity

$$R_P = (-1)^{3B+L+2S}$$

- Any weakly interacting theory that tries to fix the weak scale may fulfill the above properties and have a natural DM candidate.
- Since the DM particles are not detected, they can be found at colliders, through processes involving missing energy and momentum, in a way similar to the neutrino discovery.

Dark Matter in SUSY Theories is a neutral partner of either the Higgs or Gauge Bosons

Future Colliders : Direct Production Limits

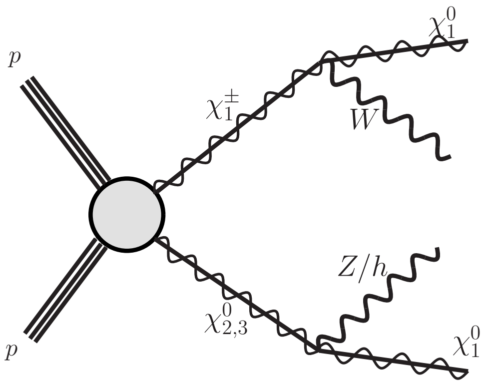


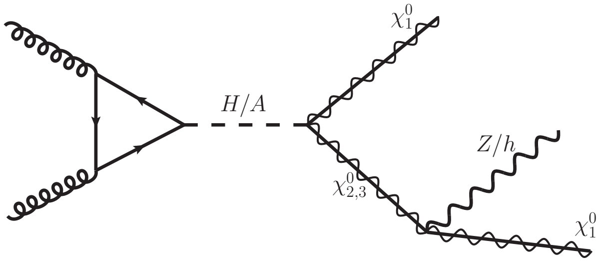
Low, Wang'14

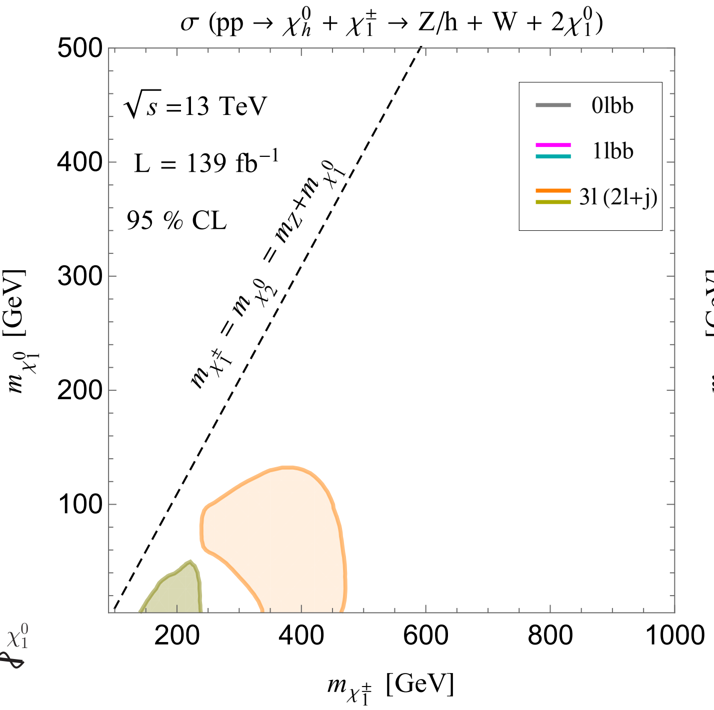
100 TeV collider will probe most promising regions

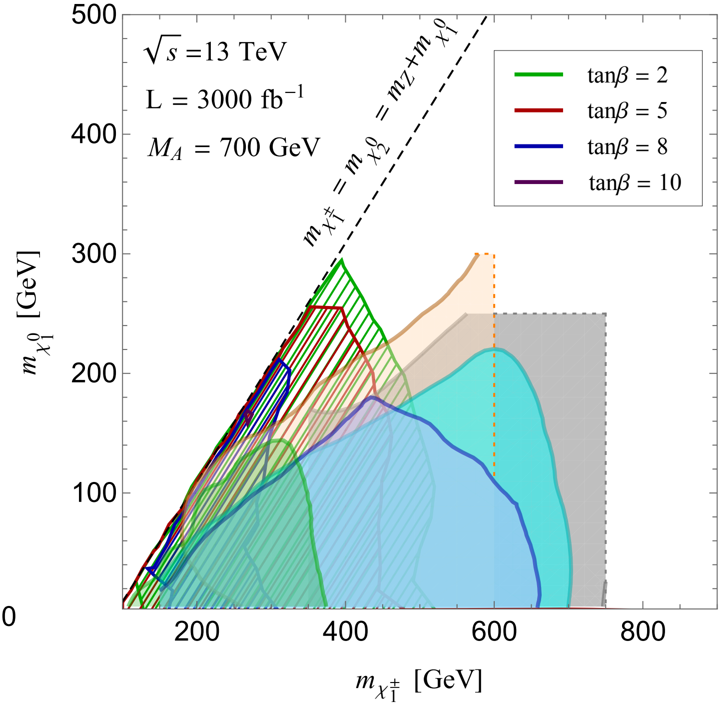
Collider Searches of Dark Matter sector at the LHC : Combination of Different Channels in Higgsino-Bino Scenario

Allows to probe potential
DM particle in a large range of masses





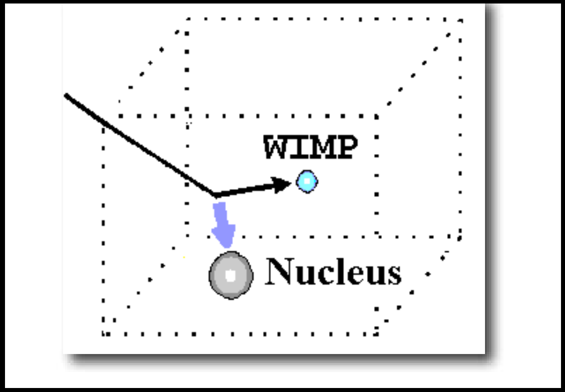


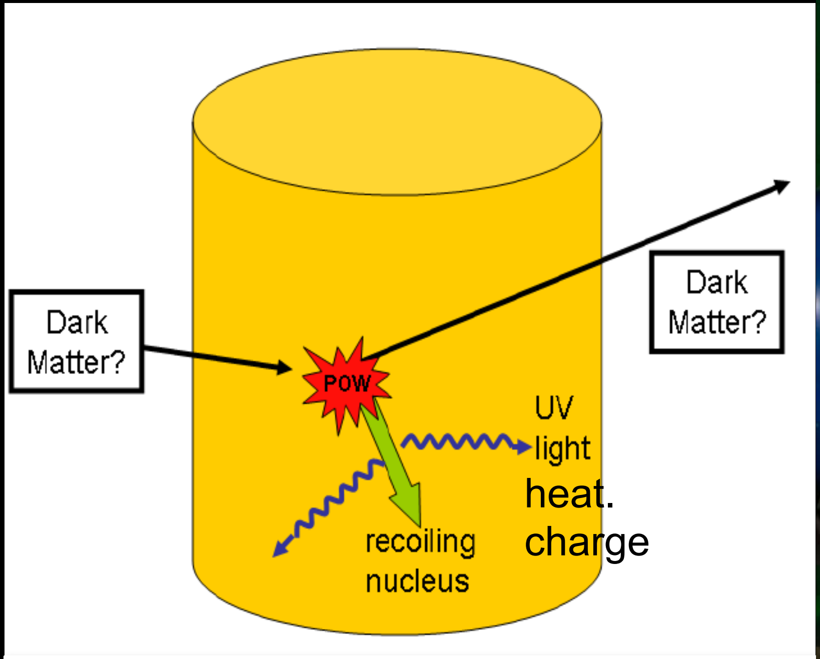


Jia Liu, Navin McGinnis, Xiaoping Wang, C.W. , 2006.07389

Dark Matter Search in Direct Detection Experiments

It can *collide with a single nucleus in your detector*





Underground detector

XENON, LUX

COUPP

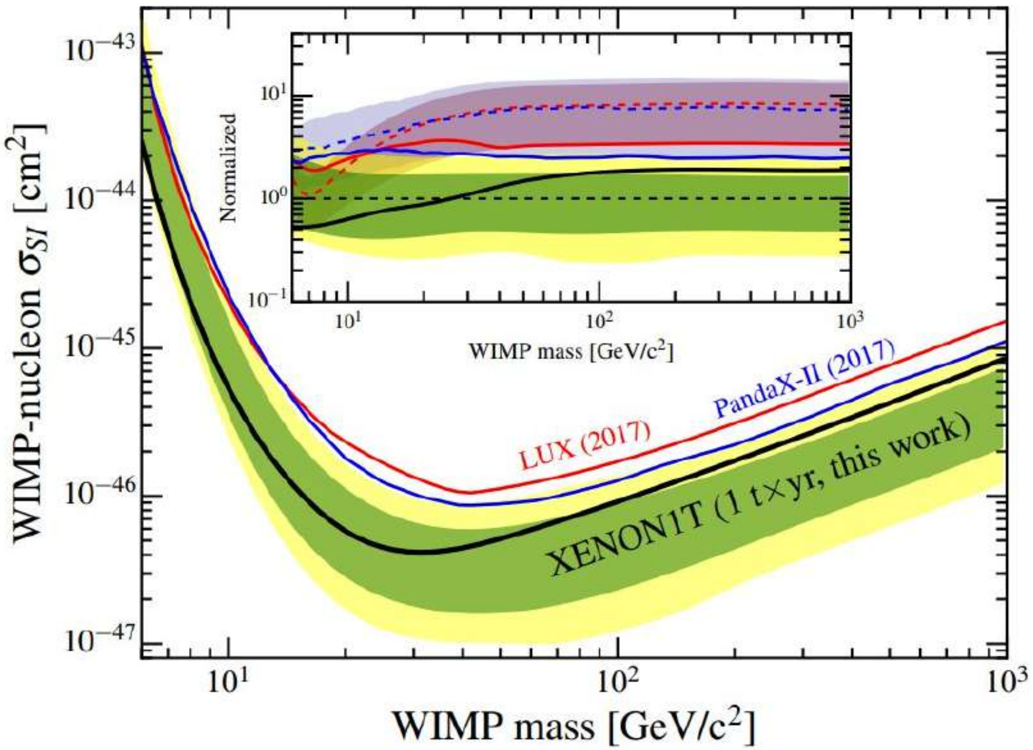
CDMS

also GoGeNT
DAMIC
DarkSide

Current Bounds from Direct Dark Matter Detection

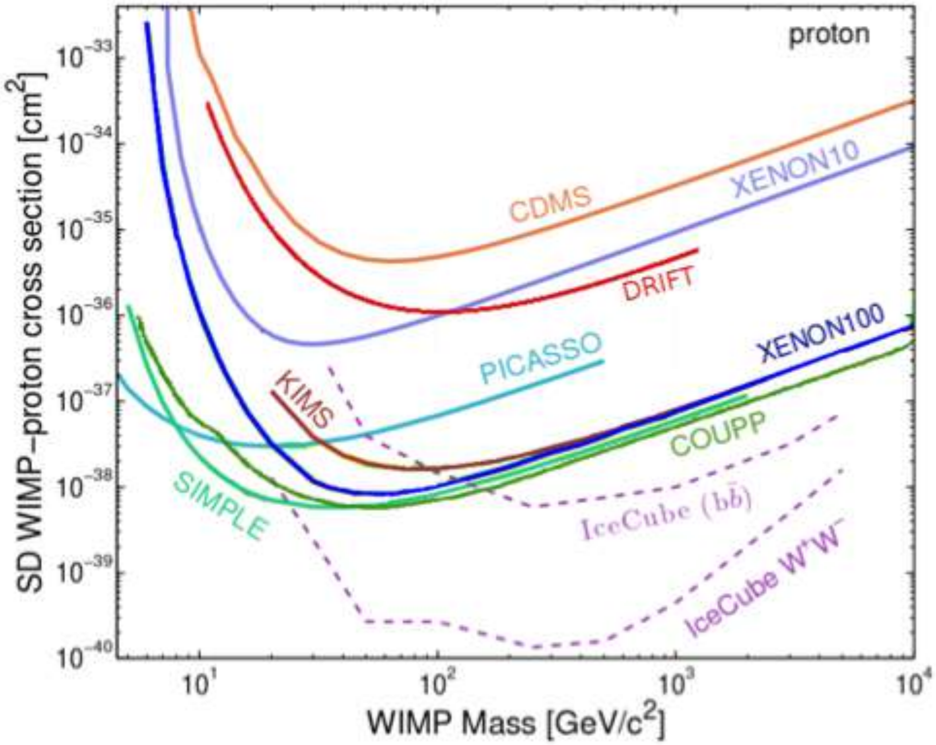
Current Limits

$$1\ \mathrm{pb} = 10^{-36}\ \mathrm{cm}^2, \qquad 1\ \mathrm{zb} = 10^{-45}\ \mathrm{cm}^2$$



Spin Independent Interactions

Xenon1T sees Moderate Excess in the WIMP region

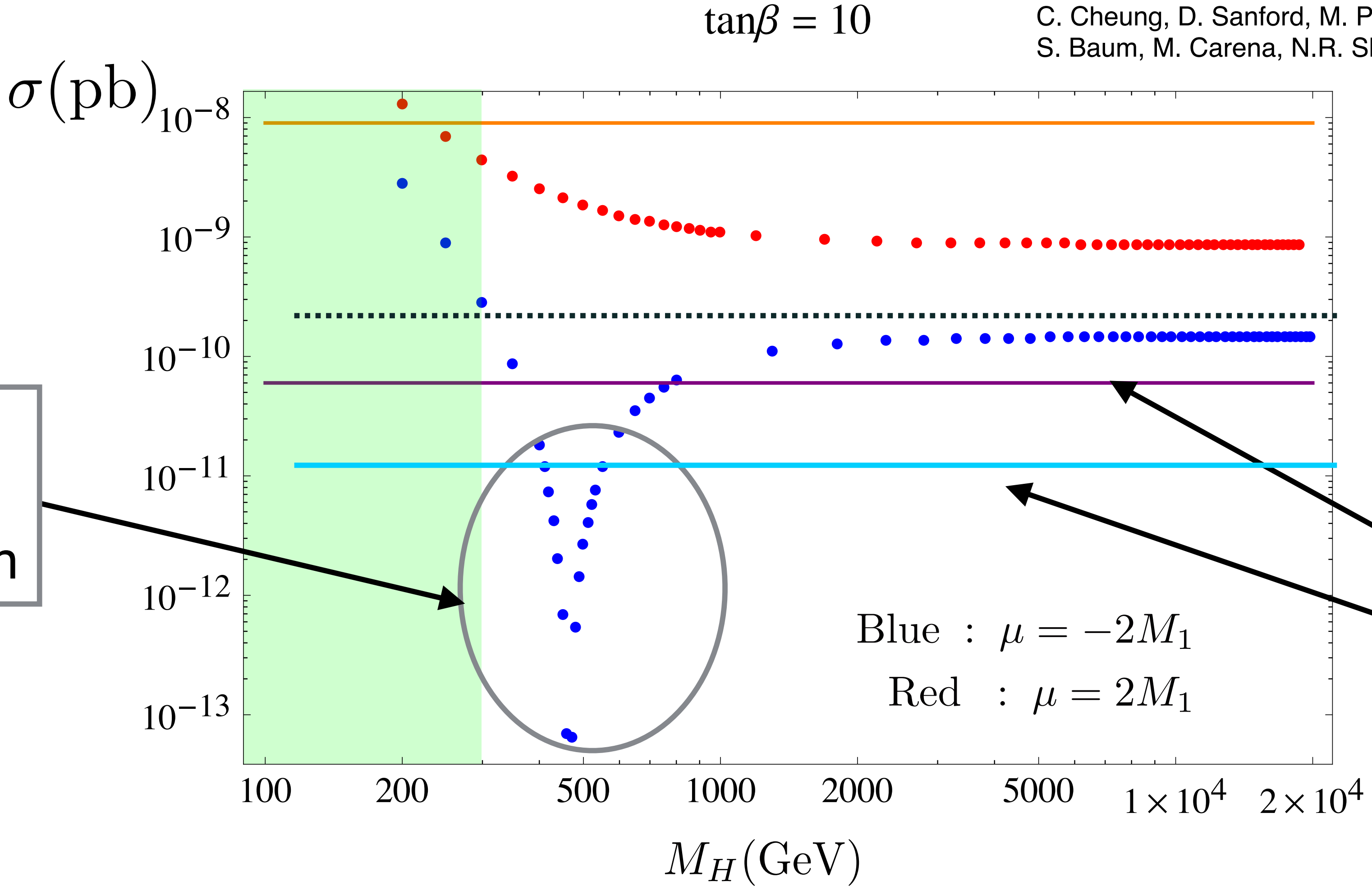


Spin Dependent Interactions

Supersymmetry Case :
Dependence of the cross section on the heavy Higgs mass

Blind Spots : $$2\left(m_{\chi^0} + \mu \sin 2\beta\right)\frac{1}{m_h^2} = -\mu \tan\beta \frac{1}{M_H^2}$$

C. Cheung, L. Hall, D. Pinner, J. Ruderman’12
P. Huang, C.W.’14
P. Huang, R. Roglans, D. Spiegel, Y. Sun, C.W.’17
C. Cheung, D. Sanford, M. Papucci, N.R. Shah, K. Zurek
S. Baum, M. Carena, N.R. Shah, S. Baum ‘18



Current Bound

Blind Spot Region

Sensitivity (Xenon1T, LZ)

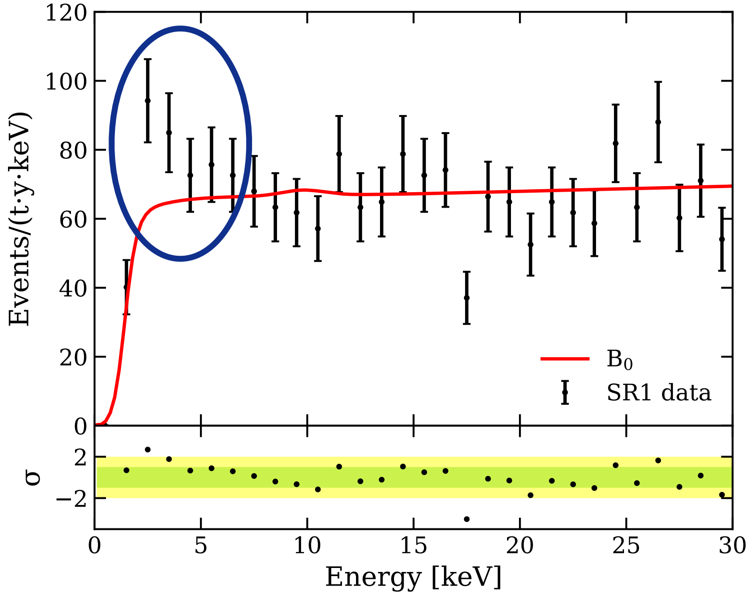
$$m_{\chi^\pm} = |\mu|, \quad m_\chi^0 = M_1, \qquad M_1 = 200\ \mathrm{GeV}$$

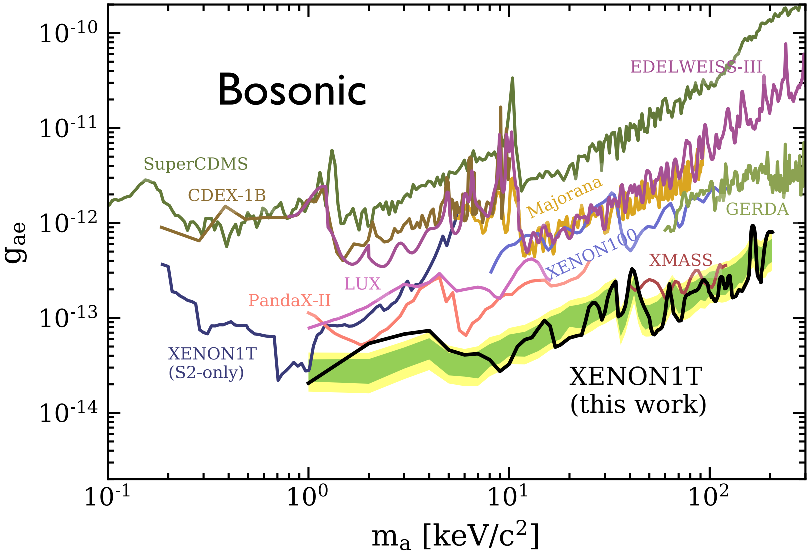
Xenon1T observation of Electron Recoil Excess

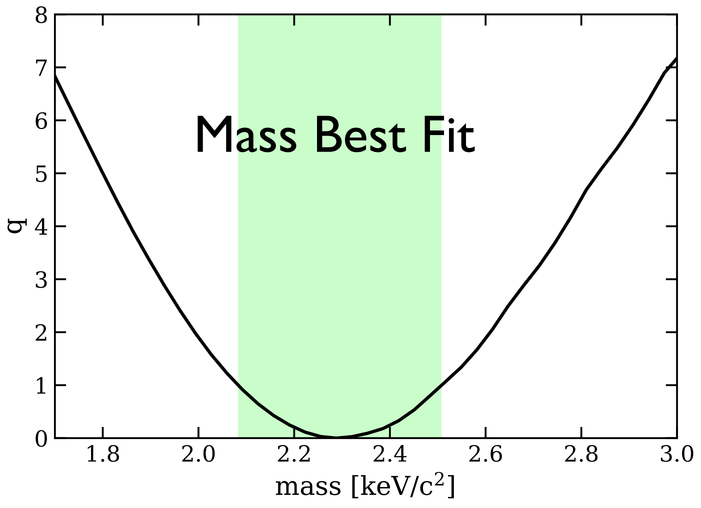
2006.09721
(and tens of recent citations)

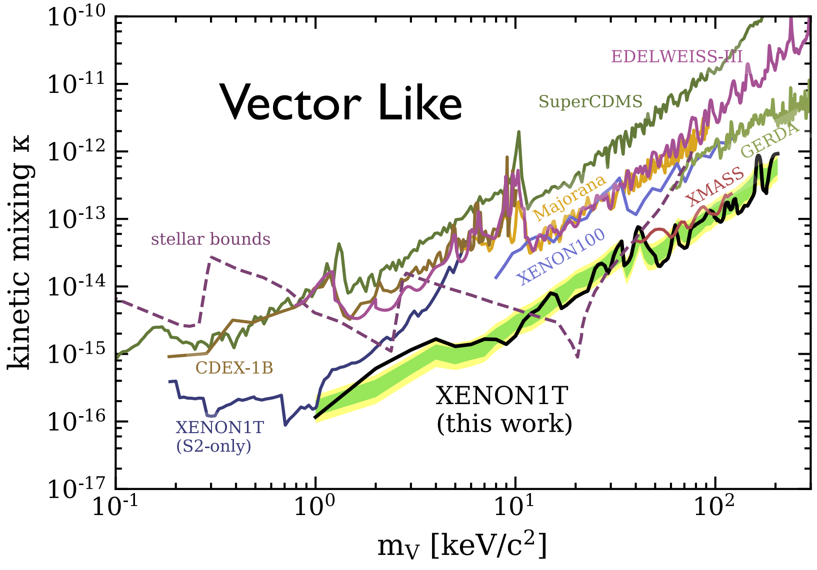
Could be Dark Matter !
Far from the WIMP region

Excess of Events





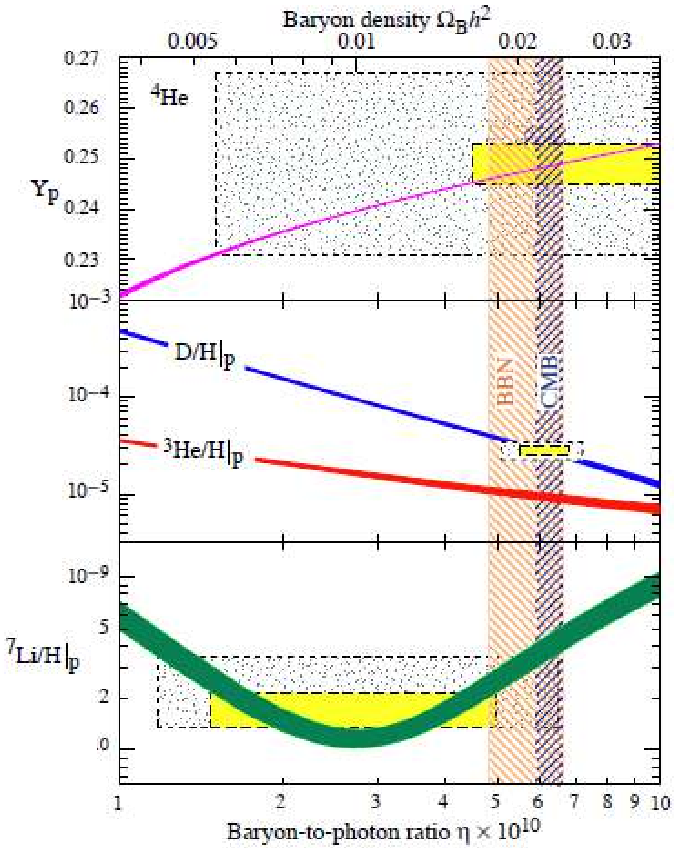




Open Question :
Origin of Ordinary Matter

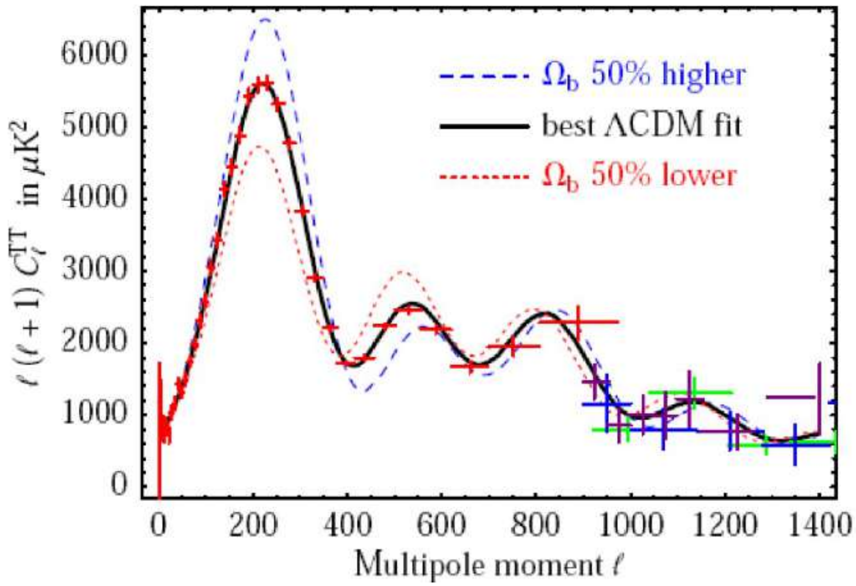
Where is the Antimatter ?

Nucleosynthesis
Abundance of light elements



Peaks in CMB power spectrum

Strumia



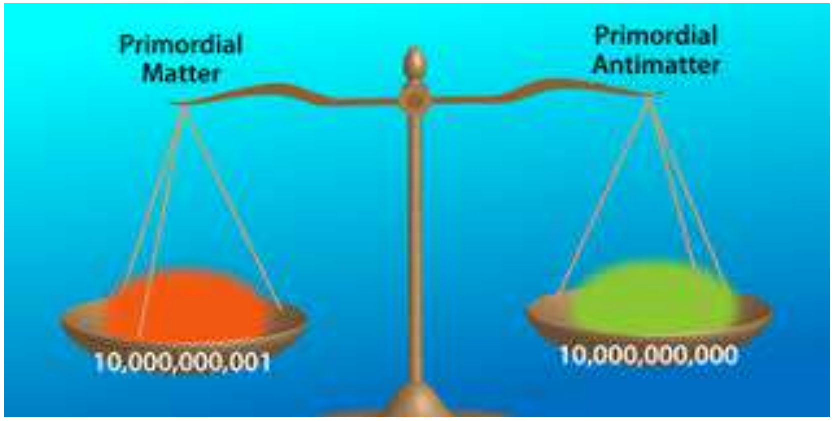
$$\boxed{\eta_B = (6.11 \pm 0.19) \times 10^{-10}}$$

$$\eta_B = \frac{n_B}{n_\gamma}$$

- How to explain the appearance of such a small quantity ?

Generating the Matter-Antimatter Asymmetry

Antimatter may have disappeared through
annihilation processes in the early Universe



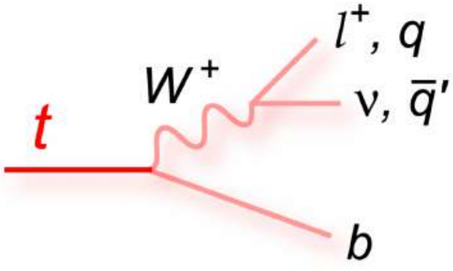
Sakharov's Conditions

- Baryon Number Violation (Quarks carry baryon number 1/3)
- C and CP Violation
- Non-Equilibrium Processes

These three conditions are fulfilled in the Standard Model

Adler, Bardeen, Bell, Jackiw ‘69

Baryon Number Violation : Anomalous Processes



In the Standard Model, all processes we see conserve both baryon and lepton number :

For gauge theories, one finds the violation of classically preserved symmetries due to the quantization process : Anomalies.

For the chiral weak interactions, gauge symmetry preservation demands that the non-conservation of baryon and lepton currents

$$\partial_\mu j^\mu_{B,L} \propto F^a_{\mu\nu} F^a_{\rho\delta} \epsilon^{\mu\nu\rho\delta}$$

$$a : \text{ Weak Interaction Indeces}$$

$$\vec{E}\vec{B}$$

Polyakov et al, t’Hooft ’75, 76

$$\tilde{F}_{\mu\nu} = \frac{\epsilon_{\mu\nu\rho\sigma}}{2} F^{\rho\sigma}$$

$$\text{If } \int F_{\mu\nu}\tilde{F}^{\mu\nu} \neq 0 \implies \Delta Q_{B,L} \neq 0$$

Baryon Number Violation at zero and finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L.. They can proceed by the production of “sphalerons”

- At zero T baryon number violating processes highly suppressed

$$S_{\rm inst} = \frac{2\pi}{\alpha_w} \qquad \Gamma_{\Delta B\neq 0} = \exp(-2S_{\rm inst})$$

- At finite T, only Boltzman suppression

$T<T_{EW}$ $$\frac{\Gamma_{B+L}}{V} = k\frac{M_W^7}{(\alpha T)^3}e^{-\beta E_{ph}(T)} \sim e^{\frac{-4M_W}{\alpha k T}}$$

$T>T_{EW}$ $$\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln\alpha^{-1} T^4$$

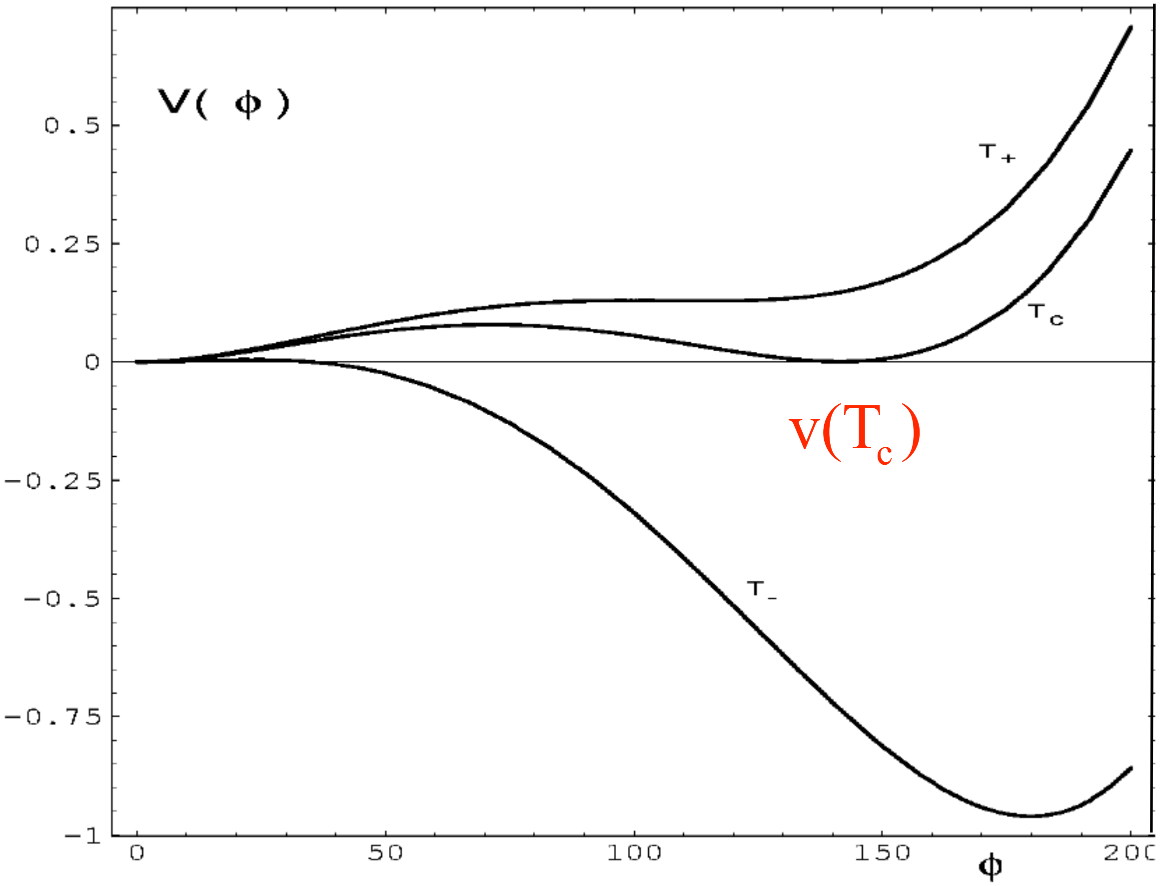
Proportional to $v(T)/T$

Klinkhamer and Manton ’85, Kushmin, Rubakov, Shaposhnikov’85, Arnold and Mc Lerran ’88

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order

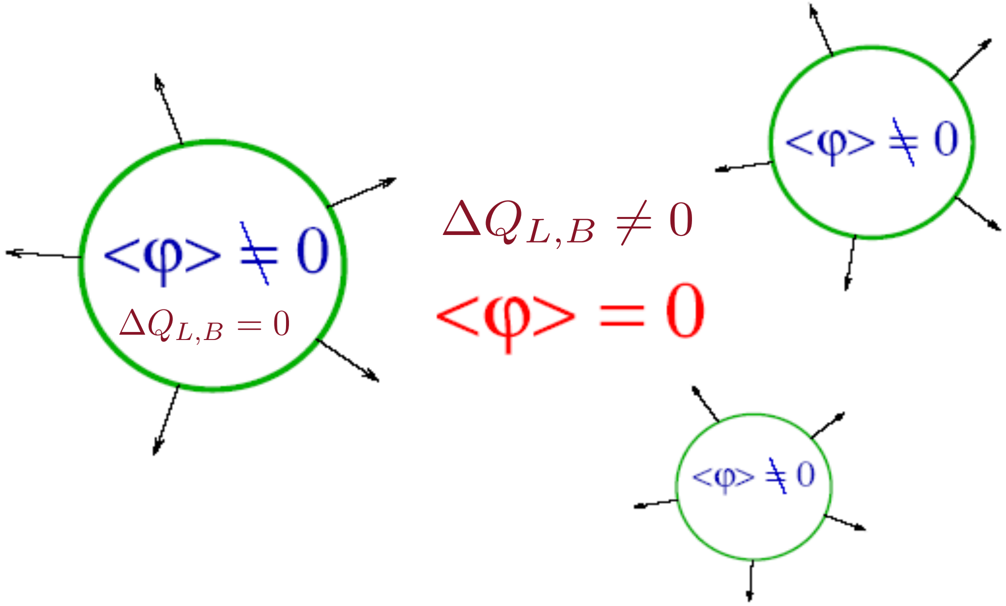
Phase Transition



Baryon Number Generation

First order phase transition :

Baryon number is generated by reactions in and around the bubble walls.



Kuzmin, Rubakov, Shaposhinikov'87,
Dine, Huet, Singleton '92,
Anderson, Hall'92,
Cohen, Kaplan, Nelson'93,
Huet, Nelson'95

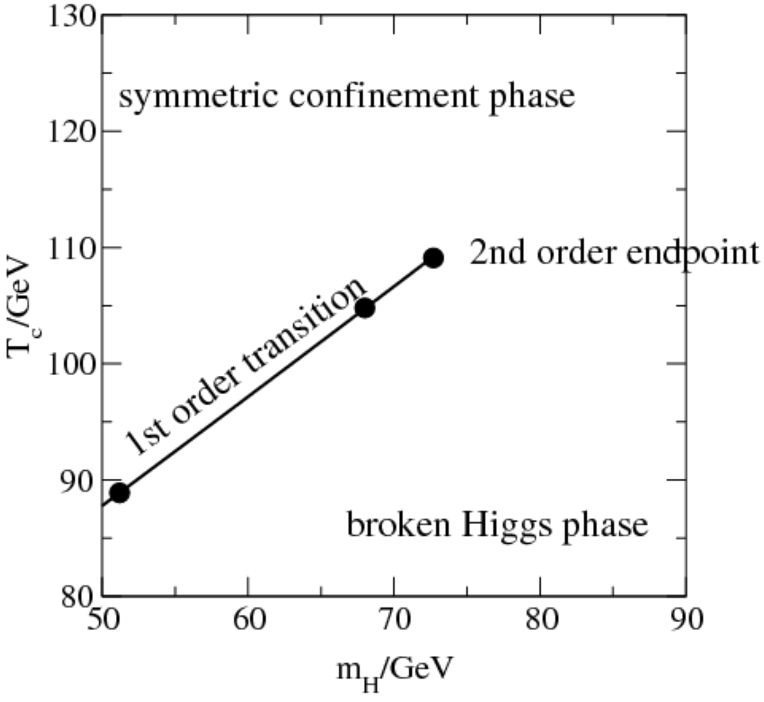
Condition for successful baryogengesis :
Suppression of baryon number violating processes inside the bubbles

$$\frac{v(T_c)}{T_c} > 1$$

Non-Equilibrium Processes :
Strongly First Order
Electroweak Phase Transition

Is this the way the Standard Model generates the asymmetry ?

- It turns out that if the Higgs mass would have been lower than 70 GeV, the phase transition would have been first order



- But the Higgs mass is 125 GeV, and the electroweak phase transition is a simple cross-over transition. Making the phase transition strongly first order requires new physics.

Models of Electroweak Baryogengesis

- Many models were written. There are nice reviews, for instance,
  Cohen, Kaplan, Nelson'93, Troden'98, D.E. Morrissey and J. Ramsey-Musolf, 1206.2942

- They are characterized by the appearance of a barrier between the rival and physical minima at either zero or finite temperature.

- Generation of barriers at finite temperature need the presence of light particles strongly coupled to the Higgs and are therefore constrained by the LHC. One example is the light stop scenario, which is currently ruled out

  Carena, Quiros, C.W.'96, Delepine et al'96, Cline et al'99, Huber and Schmidt'00,
  Carena, Quiros, Nardini, C.W.'09, Cohen et al'12, Curtin et al'12

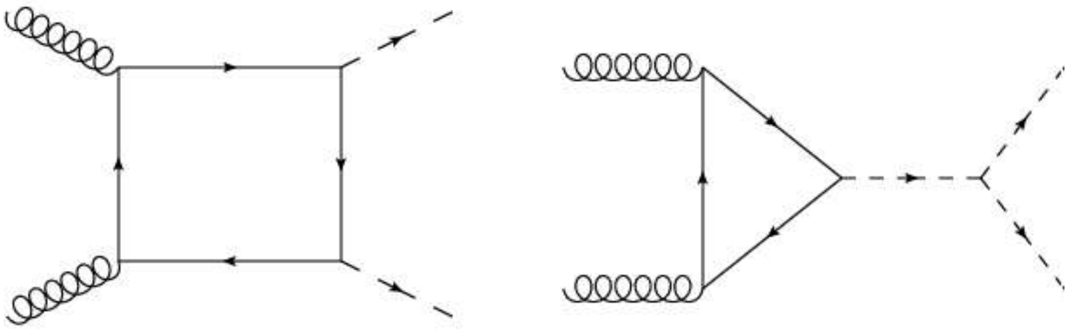
- There are models also with heavy fermions. Megevand et al'04, Fok et al'07, Katz et al'14

- Models with barriers at zero temperature have the advantage that need only weakly coupled particles, but a possible problem is that the barrier prevents the transition, even if the physical minimum is the deeper one.

  Pietroni'93, Davies et al'96, Huber et al'00,
  Menon et al'04, Carena et al'12, Kosaczuk et al'15,
  Athorn et al'19, Baum et al, to appear

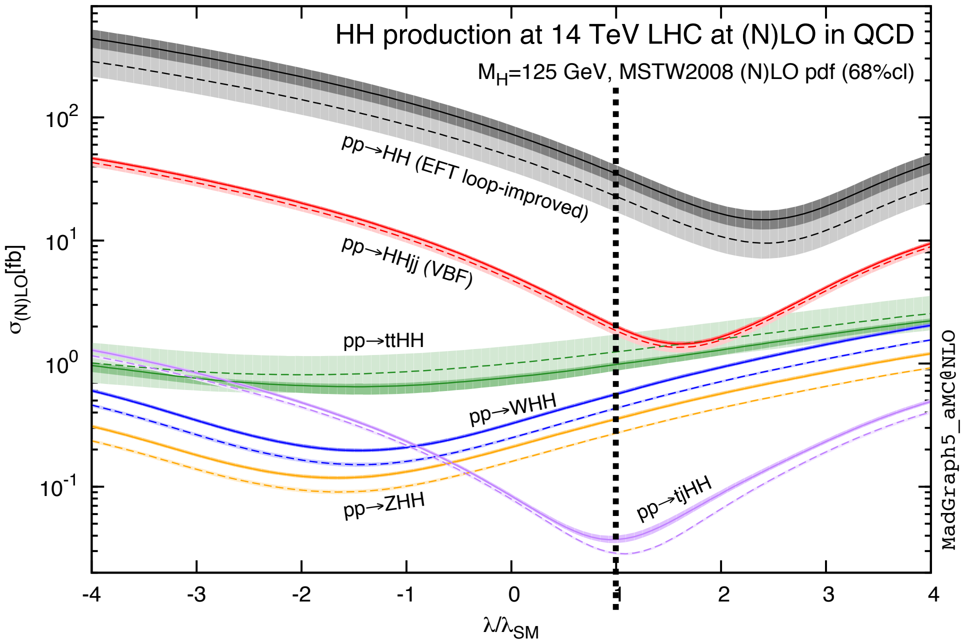
Main signature : New bosons or fermions at the weak scale (LHC)

Additional Signature : Higgs Potential Modification
Variation of the trilinear Higgs Coupling



Double Higgs Production

Frederix et al'14



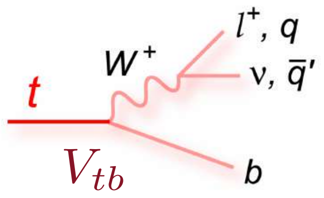
Curtin et al'14
Joglekar, Huang, Li, C.W. 1512.00068,
Huang, Long, Wang 1608.06619,
Carena, Liu, Rimbeau 1801.00794

We will start to probe this scenario at the HL-LHC, but only a higher energy collider will lead to a definite answer

CP Violation

- CP violation is induced by complex phases in the Yukawa interactions of quarks and leptons with the Higgs field. 3 Generations are necessary !

Kobayashi, Maskawa'73. 2008 Nobel Prize (together with Nambu)



$$M^f_{\rm diag} = V^f_L \; Y_f \; V^{f\dagger}_R \; \frac{v}{\sqrt{2}}$$

- It is always proportional to the so-called Jarlskog's invariants that is proportional to the mixing angles appearing in W interactions…

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + {\rm h.c.}, \qquad V_{\rm CKM} \equiv V^u_L V^{d\dagger}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$J = c_{12}c_{13}^2 s_{12}s_{13}s_{23}\sin\delta$$

δ : CP violating phase

Does Nature uses this SM CP Violation ?

- In spite of the fact that CP-violation is the only apparent reason nature chose three generations, it does not seem to be used for baryogenesis.

- The baryon number generated at a phase transition would be several orders of magnitude lower than what is necessary.

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}}\frac{\alpha_W T}{32\sqrt{\alpha_s}}\right]^3 J\,\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\,\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

Gavela, Hernandez, Orloff, Pene, Quimbay’94

- In the quark sector, .

$$J = 3\times 10^{-5},\;\; \gamma \simeq 100\ \mathrm{GeV}$$

- New sources of CP violation are necessary.

New CP Violating Phases

- One natural consequence of these phases are Electric Dipole Moments.
- Electric dipole moments violate P and CP symmetries.
- The intrinsic electric dipole moment d for elementary particles is defined with respect to its reaction to an electric field (spin 1/2) :

$$H = -\mu \left(\frac{2}{\hbar} \vec{S} \right) \vec{B} - d \left(\frac{2}{\hbar} \vec{S} \right) \vec{E} \qquad \mu \frac{2}{\hbar} = \frac{q}{2m} g$$

	$d\vec{S}$	$\mu\vec{S}$	$\vec{E}$	$\vec{B}$	$d\vec{S}\vec{E}$	$\mu\vec{S}\vec{B}$
P	+1	+1	-1	+1	-1	+1
T	-1	-1	+1	-1	-1	+1
C	-1	-1	-1	-1	+1	+1
CPT	+1	+1	+1	+1	+1	+1

- d is zero in QED. They are induced by weak interactions

Experimental Bounds

- No electric dipole moment of the electron or the neutron has been observed.
- Determination of d relies on clever ways of measuring the variation of the precession frequency in the presence of electric fields

$$\omega = \frac{2}{\hbar}\left(\mu B \pm dE\right)$$

- Hence,

$$d = \frac{\hbar \Delta\omega}{4E}$$

- Current Bounds

$$d_e < 1.1 \times 10^{-29} \text{ e cm}$$

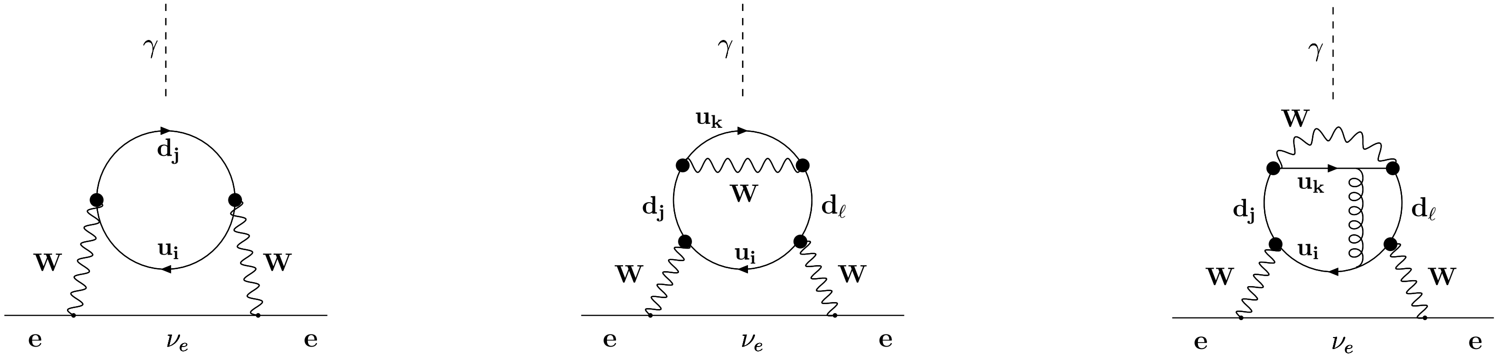
Uses polar molecules, like Thorium Monoxide, to increase electric fields

DeMille, Doyle, Gabrielse'18

Electric Dipole Moments

- What is remarkable is that the SM one, two and three loop contributions cancel,

Pospelov, Khriplovich '91



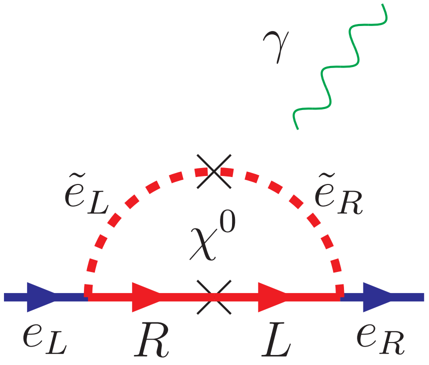
- And the first non-trivial contribution appears at four loops, and are proportional to the quark Jarlskog invariant

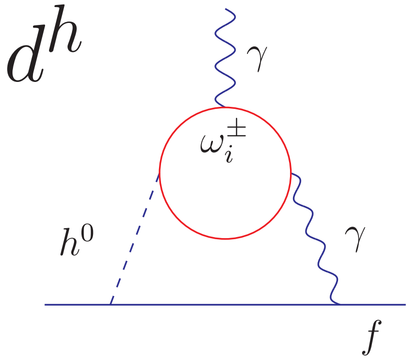
$$d_e^{(\mathrm{SM})}[\mathrm{one-gluon}] \sim \frac{\alpha_S}{4\pi} \cdot \frac{e G_{\mathrm{F}} m_e J \alpha^2}{256\pi^4} \simeq 3 \times 10^{-37} \ \mathrm{e\ cm} \qquad (m_{\nu_i} = 0 \ \mathrm{assumed})$$

- This is much lower than the current limits. Another SM triumph.

New Physics for Baryogengesis

- The list of possible new physics contributions is very large. Nice review by Pospelov'05.
- There are one and two loop contributions that may cancel, but predictions typically close to experiments bounds.





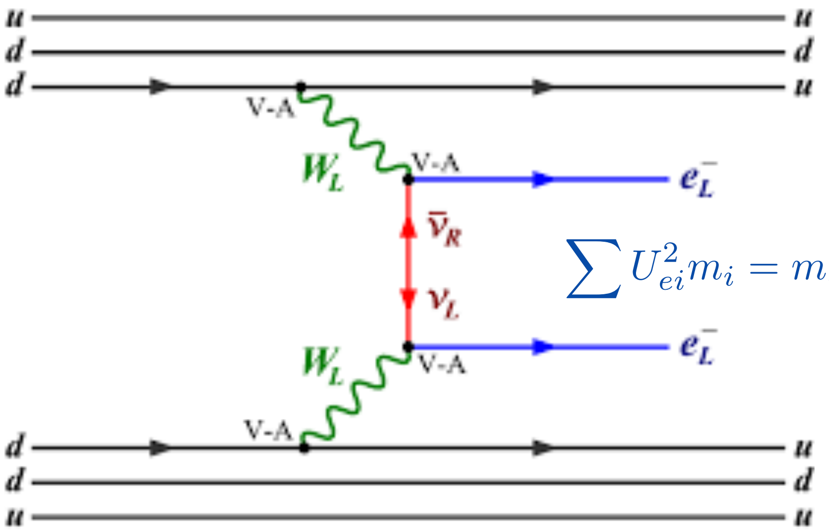
Chang, Keung, Pilaftsis'98-00, Ibrahim, Nath'00

- I encountered this problem by working on Baryogengesis scenarios and CP violation in the Higgs sector, and also last year, while trying to explain the galactic center excess from Dark Matter annihilation via the Higgs

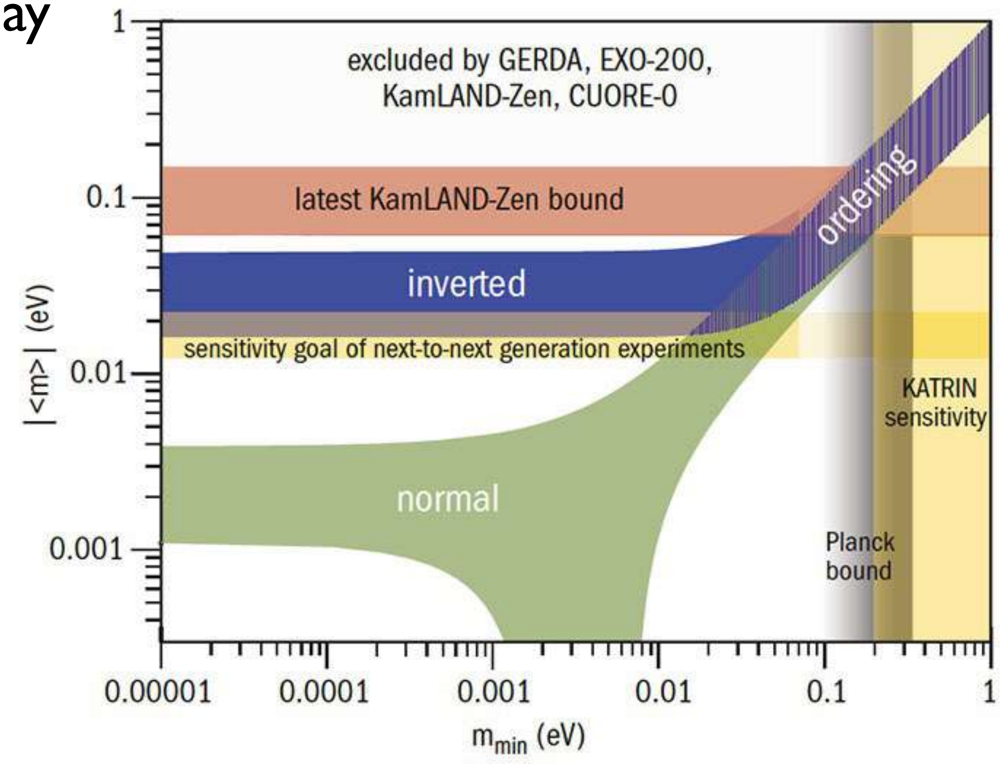
M. Carena, J. Osborne, N. Shah, C.W.'19

Open Question :
Are neutrinos there own antiparticle (Majorana)

Best test : Neutrino-less double beta decay



$$\sum U_{ei}^2 m_i = m_{ee}$$



Half-Life Limits

EXO: $T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL) ^{136}Xe WIPP
Nature, **510**, 229 (2014)

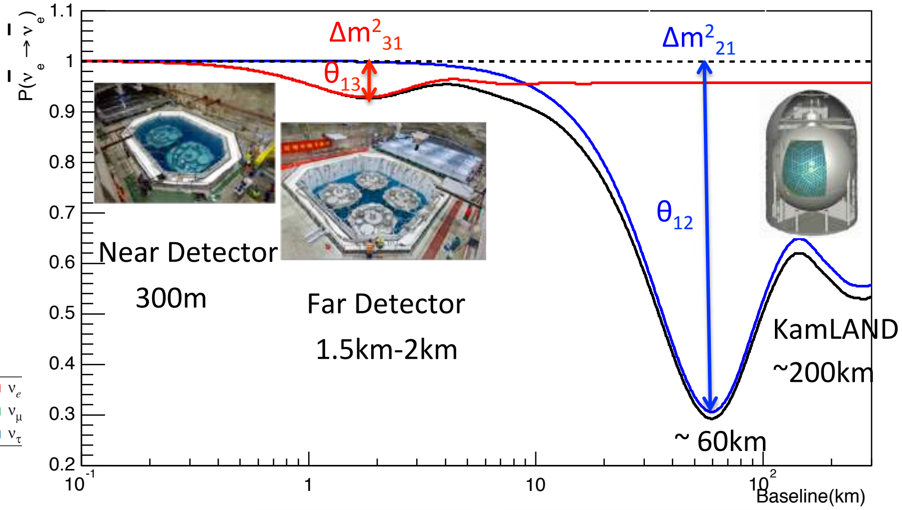
KamLAND-Zen: $T_{1/2} > 3.1 \times 10^{25}$ yr (90%CL) ^{136}Xe Kamioka
very preliminary

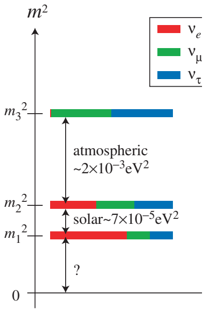
GERDA: $T_{1/2} > 2.1 \times 10^{25}$yr (90% CL) ^{76}Ge LNGS
PRL, **111**, 122 (2013)

$$\mathcal{L}_m = -\frac{m_\nu}{2}\left(\nu_L \nu_L + h.c.\right)$$

$$\Psi_M = \begin{pmatrix} \Psi_L \\ \bar{\Psi}_L \end{pmatrix}, \quad \Psi_L = \bar{\Psi}_R \implies \Psi_M = \Psi_M^C$$

Reactor Neutrino Oscillation





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \boxed{\sin^2 2\theta_{13} \sin^2 \Delta_{31}} + \boxed{\cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}}$$

Two different oscillation length scale:

- $\Delta m^2_{31} \approx 2.4 \times 10^{-3}$ eV^2
- $\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

Largely Independent θ_{13} measurement

- Capture time: 30μs (nGd) -> 200μs(nH)
- Delayed E: 8MeV (nGd) -> 2.2 MeV (nH)
- More Energy leakage at boundary

Double Chooz (Rate+Spectra):

$\sin^2 2\theta_{13} = 0.097 \pm 0.034(\text{stat}) \pm 0.034\ (\text{syst})$

Phys. Lett. B723 (2013) 66-70

Daya Bay (Rate Only) :

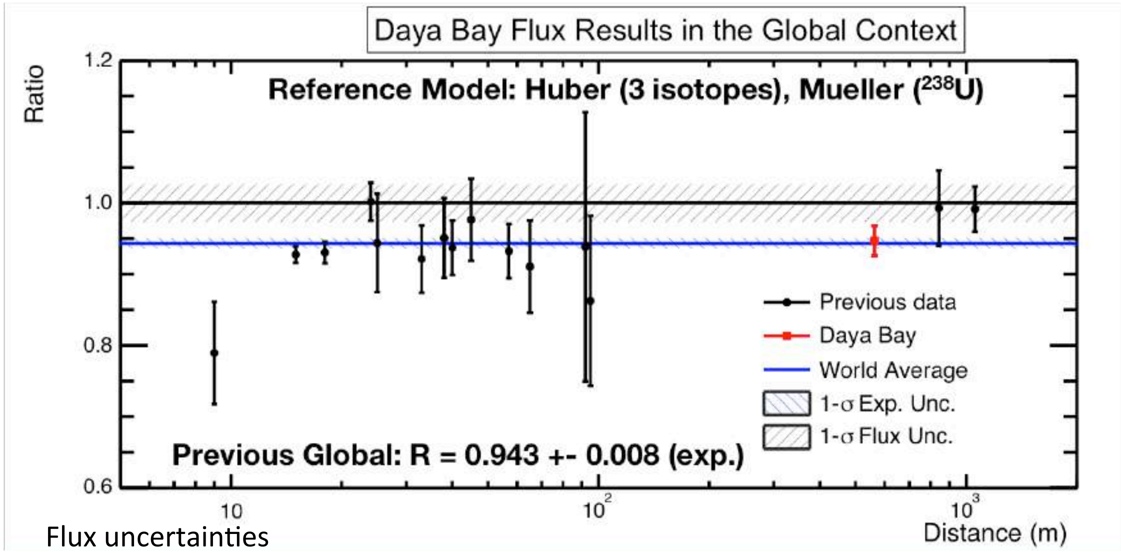
$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

arXiv: 1406.6468

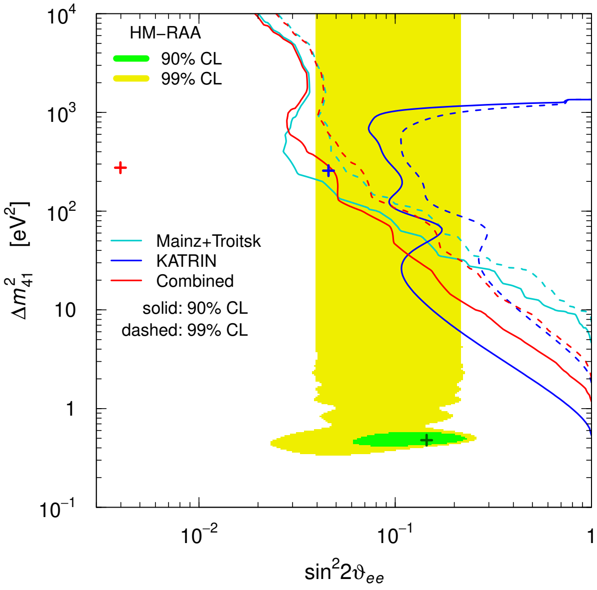
RENO (Rate Only) :

$\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat}) \pm 0.025\ (\text{syst})$

Neutrino 2014



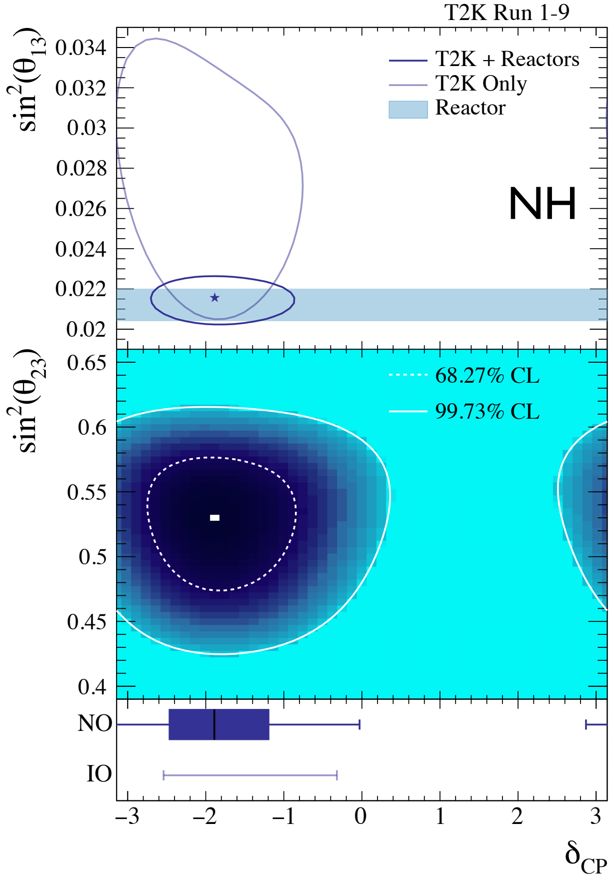
Flux uncertainties

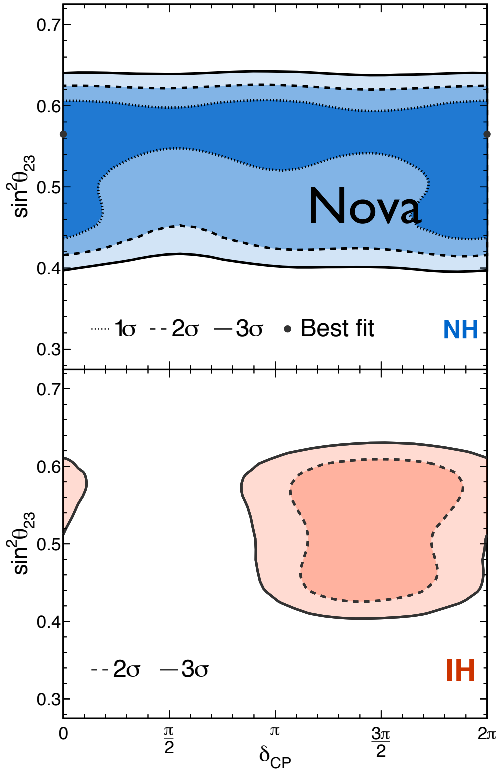


Open Question
Is CP violated in the neutrino sector ?

Best test : $\nu_\mu \to \nu_e$ oscillations. (long baseline)

Hints of sizable CP-violation





C.W. rule

$$\theta_{12} \sim 34^o$$

$$\theta_{23} \sim 45^o$$

$$\theta_{13} \sim \ 9^o$$

Anomalies at short baseline MiniBoone and LSND experiments, to be checked by the SBNP at Fermilab

Leptogenesis

Minkowski'77, Gell-Man, Ramond, Yanagida'79

- Light Neutrino Masses explained by See-saw Mechanism :
  Massive Right Majorana neutrinos of mass MN couple to the left-handed ones. If their masses are large, we see three light neutrinos

$$\boxed{0.1\ \text{eV}} \longrightarrow \mathcal{M}_\nu = M_D^T \underset{\boxed{10^{10}\ \text{GeV}}}{\underset{\uparrow}{M_N^{-1}}} M_D$$

$$\nu_i = U_{i\alpha}\nu_\alpha$$

- In the presence of CP-violation, decays of the heavy neutrinos provides the original asymmetry

Fukugita, Yanagida'86

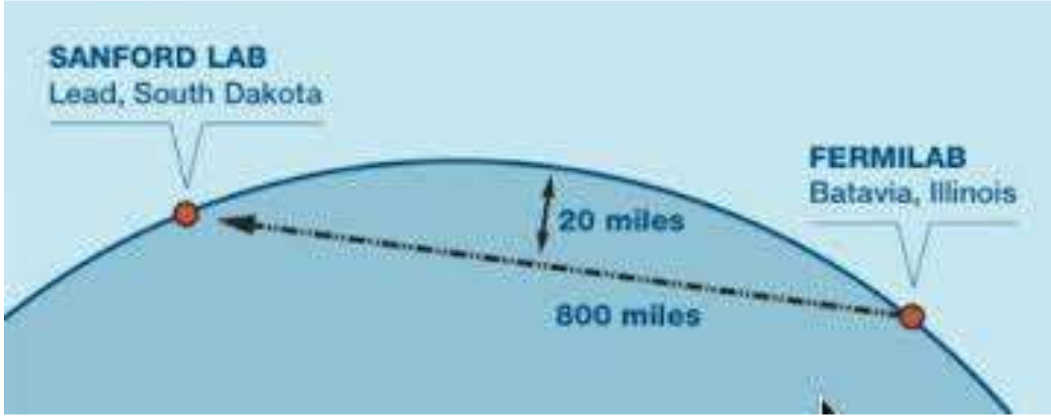
$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)}$$

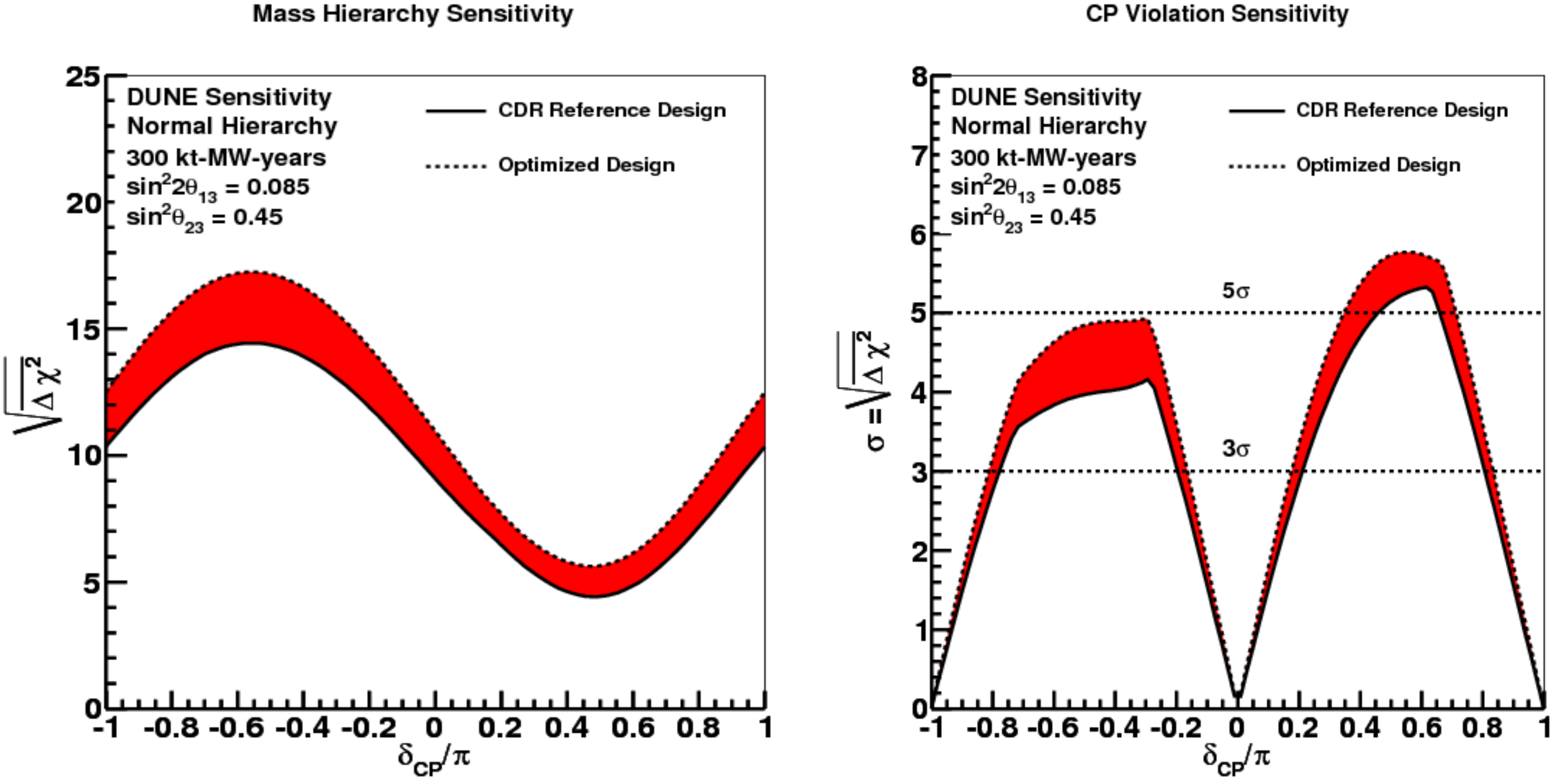
CP Violation

Harvey, Turner'90

$$B \simeq \frac{(B-L)^{\text{in}}}{3} \qquad \frac{n_B}{n_\gamma} \simeq 10^{-2}\epsilon_1$$

Future long baseline facilities : DUNE and HyperK





Open Question : The nature of Dark Energy

Einsten General Relativity contains a possible explanation of the observed exponential expansion. Is it just a cosmological constant ?

If it is, what sets its scale ? Why does it differ from the naive vacuum energy, of the order of the weak or GUT scales ?

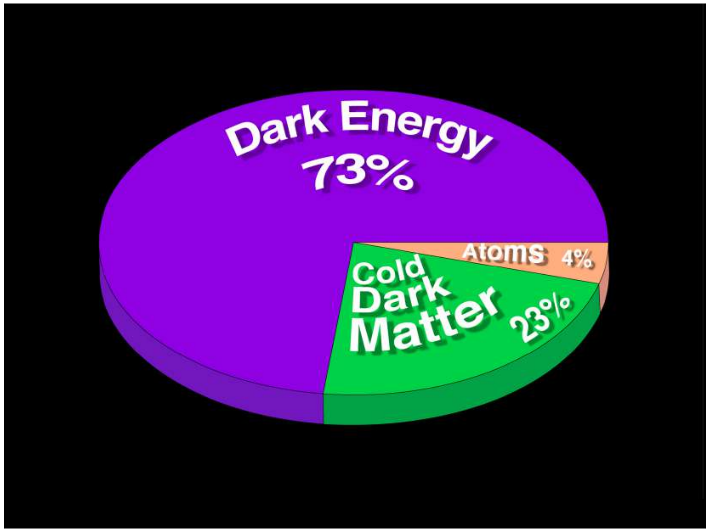
If it is not, what sets its scale and time variation ?

$$H^2 = \frac{8\pi G}{3}(\rho + \rho_\Lambda)$$

$$\rho = \rho_{\rm rad} + \rho_M$$

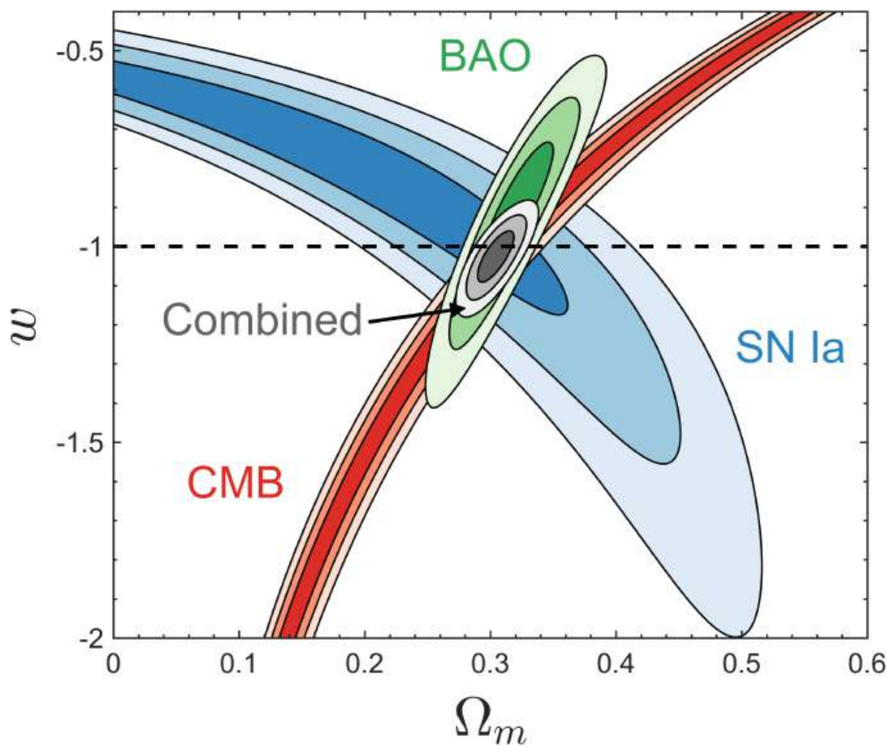
$$\rho_{\rm rad} = \frac{\rho^0_{\rm rad} a_0^4}{a^4}, \quad \rho_M = \frac{\rho^0_M a_0^3}{a^3}, \quad \rho_\Lambda = \rho^0_\Lambda$$

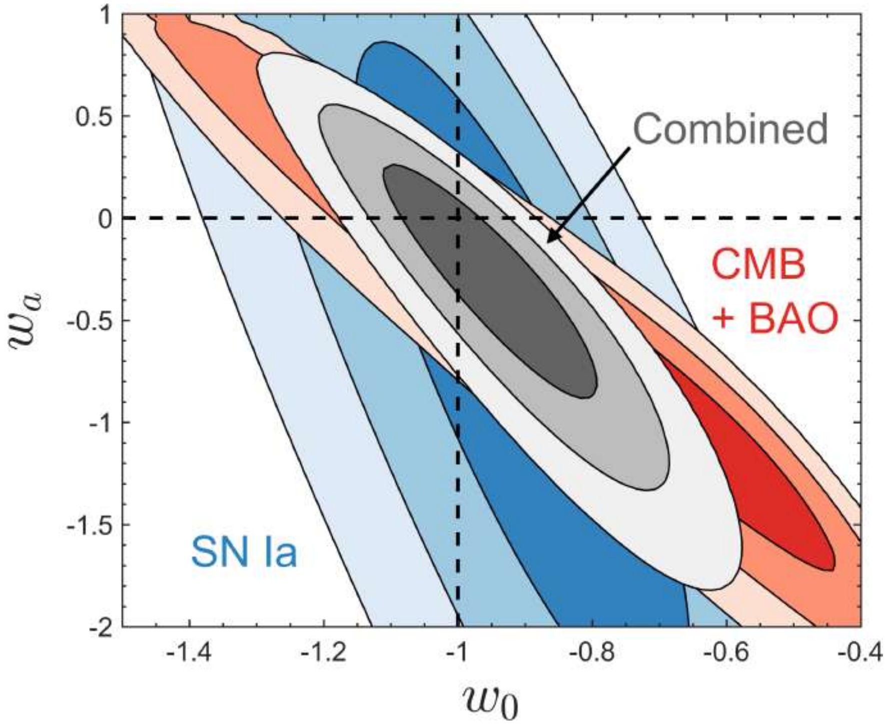
$$\rho_\Lambda \simeq (10^{-3}{\rm eV})^4, \quad \Lambda = 8\pi G \rho_\Lambda \simeq \left(10^{-33}{\rm eV}\right)^2$$



Coincidence Problem ?

Current Experimental Constraints





$$w = \frac{p}{\rho}, \qquad w = w_0 + w_a(1-a)$$

$$R_{\mu\nu} - \frac{1}{2} R \; g_{\mu\nu} = 8\pi G \; T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Sign convention

$$g_{\mu\nu} = (-1, 1, 1, 1)$$

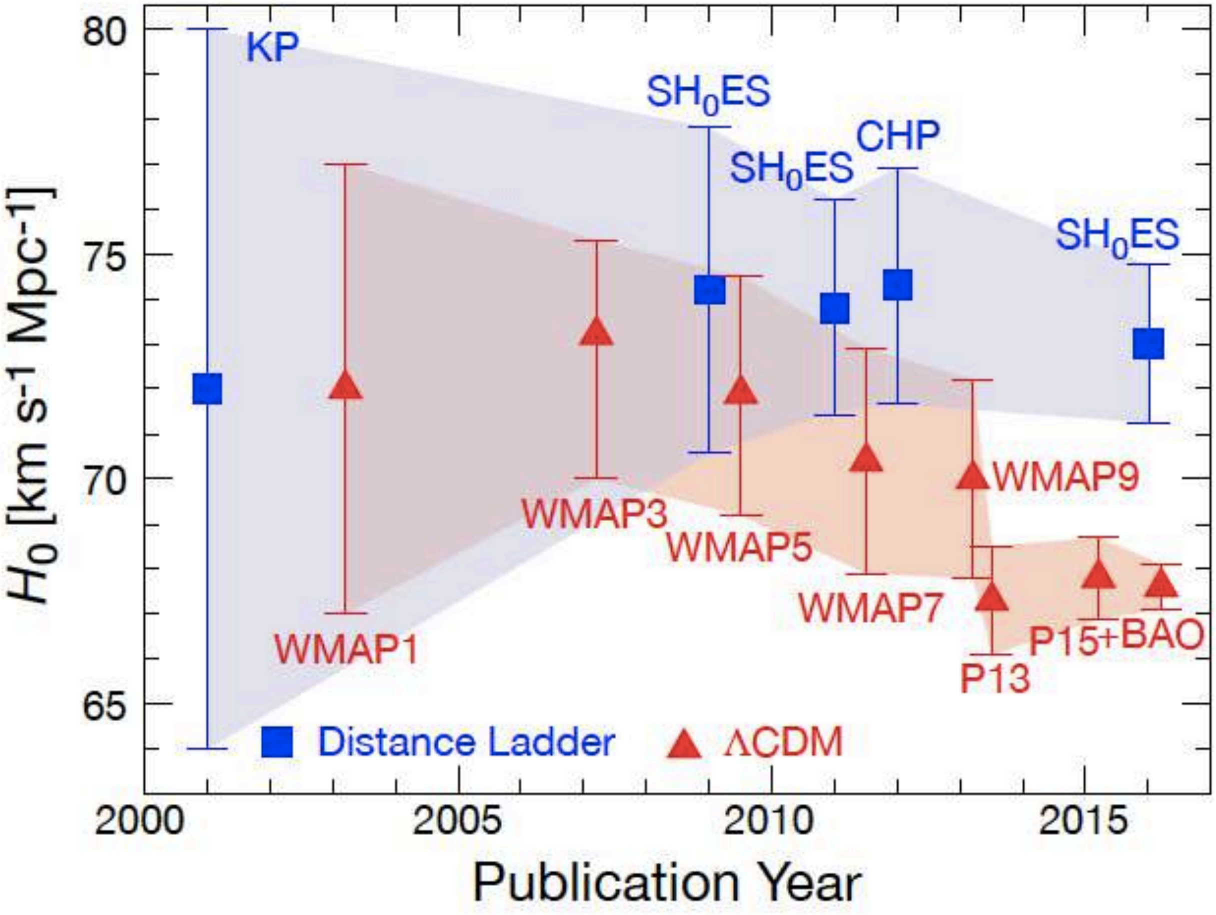
$$\rho_\Lambda \simeq (10^{-3}\mathrm{eV})^4, \quad \Lambda = 8\pi G \rho_\Lambda \simeq \left(10^{-33}\mathrm{eV}\right)^2$$

Time variation of Dark Energy may be related to tension in determination of Hubble rate

Karwal and Kamionkowski'16, Sakstein, Trodden '19

Tension in the determination of the Hubble rate

W. Friemann'17



Many other Open Questions Remain

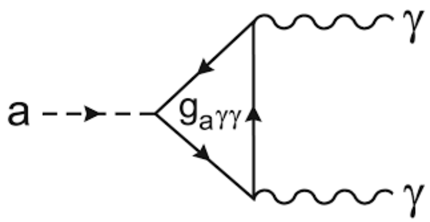
- Open Question VII : Is the Proton Stable ?
  Probably not. In Grand Unified Theories one gets interactions that transform quarks into leptons, making the decay of protons into positrons and neutral mesons possible ! (Langacker'81)
  We will be looking for these decays in the next generation of neutrino experiments, DUNE (Fermilab) and HyperK.

- Open Question VIII : Is CP violated in the strong interactions ?
  It could be, but it would lead to neutron electric dipole moments much larger than the current experimental bound unless the up quark mass is very small or a new field and particle, the Axion, is introduced.
  Peccei, Quinn'77, Weinberg, Wilczek;78.

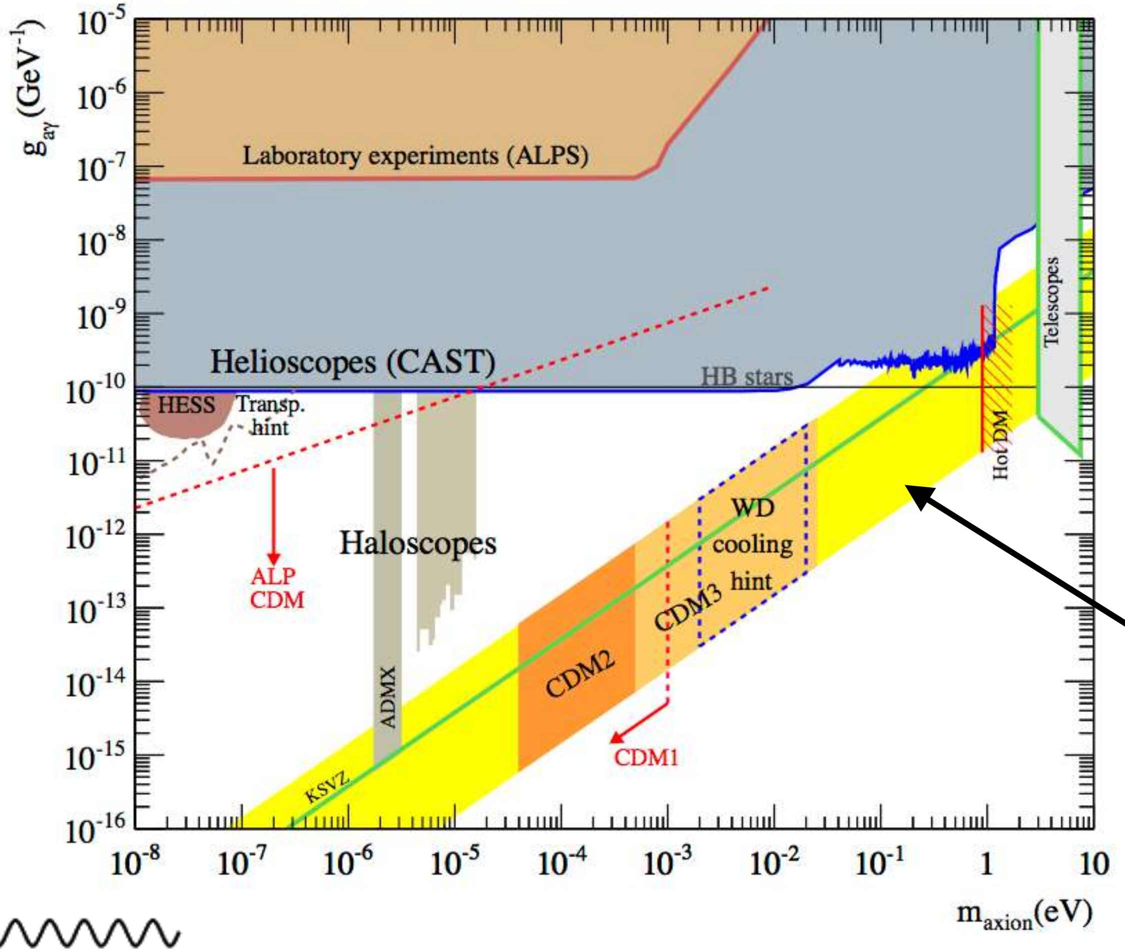
- But may be the up quark is small and connected with the neutrino masses. In this case, one predicts an observable neutron electric dipole moment.
  Kaplan, Manohar'86, Agrawal, Kyle'18, Carena, Liu, Liu, Shah, Wang, C.W.'19

Axions : Solve the strong CP Problem
They are also a good CDM candidate

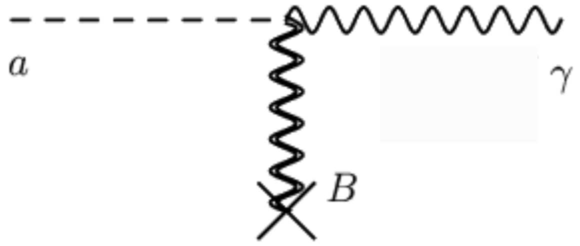
- Peccei, Quinn’77, Weinberg, Wilczek;78.



Helioscopes :
Axion produced
in solar core
(conversion to
X Rays)



QCD
Axion



Hallo Axions : Resonant
Magnetic Cavity Searches

Conclusions

- Particle physics has advanced through a combination of great theoretical ideas and exceptionally clever experiments.
- The Standard Model is a has non-obvious properties like confinement, spontaneous breaking of symmetries, violation of parity and time reversal symmetries, tiny neutrino masses, etc
- Many of these properties serve to define the Universe in which we live, but Nature seems to rely on physics beyond the Standard Model.
- We are still at odds in finding out what is this theory, but some hints like Dark Matter and baryogengesis have been provided to us.
- Maybe the marriage with gravity, through cosmology, will provide alternative clues.
- An active experimental program is in progress. May it lead us to discovery and to the path for a deeper understanding of Nature.

Backup Slides

Long Base-line Neutrino Experiments and CP-violation

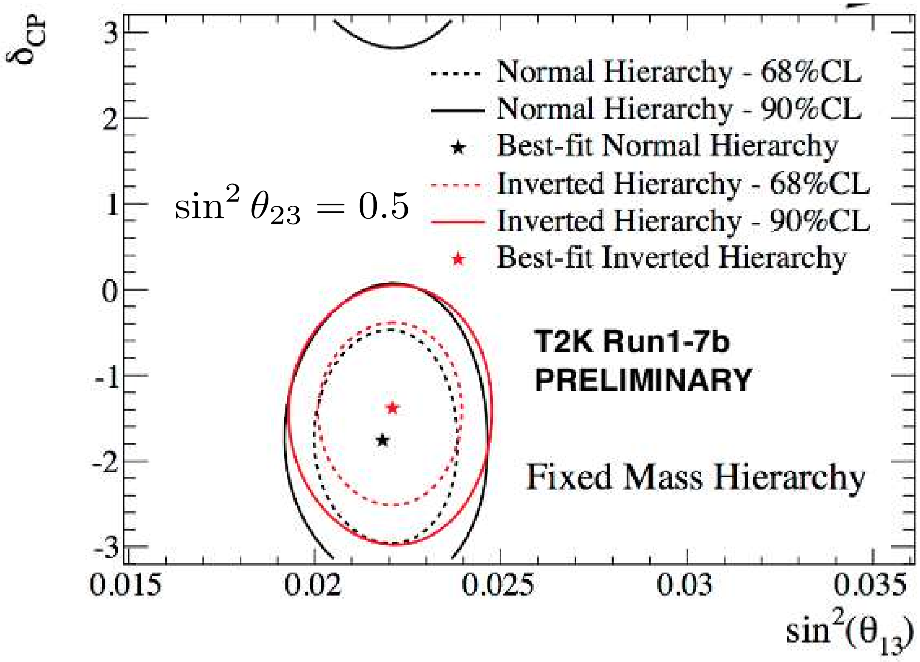
$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2\theta_{23}}{(A-1)^2} \cdot \sin^2\left((A-1)\Delta m^2_{31} L/4E\right)$$

$$-\frac{|\Delta m^2_{21}|}{|\Delta m^2_{31}|} \frac{\boxed{\sin\delta} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13}}{A(1-A)} \sin\Delta \sin(A\Delta) \sin((1-A)\Delta)$$

$$A = \sqrt{2} G_F N_e \frac{2E}{\boxed{\Delta m^2_{31}}} \longleftarrow \text{hierarchy}$$

where $\Delta = \Delta m^2_{31} L/4E$

Hints of sizable CP-violation



$\theta_{12} \sim 34^o$

$\theta_{23} \sim 45^o$

$\theta_{13} \sim 9^o$

CP violation in the QCD sector

- $F_{\mu\nu}\tilde{F}^{\mu\nu}$ is Lorentz invariant but violates CP.

The question is why this is not present in the QCD Lagrangian. Actually, it is natural to expect that the QCD Lagrangian density contain terms

$$\mathcal{L} \supset -\frac{\theta\ g_s^2}{32\pi^2} G_{\mu\nu,a}\tilde{G}^{\mu\nu,a} - \sum_q (m_q \bar{q}_L q_R + h.c.)$$

The presence of the CP violating term would induce an electric dipole moment for the neutron.

$$d_n \sim \theta_{\rm QCD} \times (2.4 \pm 0.7) \times 10^{-16}\,{\rm e\ cm},$$

But experimentally, we know that

$$d_n^{\rm exp} < 3 \times 10^{-26}\ {\rm e\ cm}$$

So, why is $\theta_{\rm QCD} < 10^{-10}$?

Do we need new physics to explain the smallness of θ ?

Actually, it turns out that θ is modified by chiral phase transformations of the quark fields and the only physical quantity is

$$\theta_{\rm QCD} = \theta + \arg[det[M_q]]$$

By suitable rotations one can go to a basis in which

$$\theta_{\rm QCD} = \arg[m_u]$$

and the bound would read,

$$\mathrm{Im}[m_u(1\mathrm{GeV})] < 10^{-3}\mathrm{eV}$$

So, a massless up quark would solve the problem, but apparently the up-quark mass is a few MeV.

Last year, we spent some time considering scenarios in which the imaginary part of the up-quark mass remains small, connecting it withe the small neutrino masses, and hence getting a prediction for the neutron electric dipole moment !

M. Carena, D. Liu, J. Liu, N. Shah, X. Wang, C.W.'19

Asymmetric Dark Matter and Baryon Number

- The idea is to explain the intriguing relation between the abundances of ordinary matter and Dark Matter
- Dark Matter, could carry a conserved quantum number; it could be a baryon of a different neutral sector

  Nusinov'85, Barr'91, Kaplan'92, Dodelson et al'92
- Dark Matter and baryon (or leptons) can proceed from similar processes, like the decay of a heavy neutral state
- The number densities would be related. What about the masses ?
- Beautiful idea by Bai and Schwaller'12, relying on IR fixed points, relating the QCD scale to the Dark Sector QCD. States charged under both sectors, with masses of a few TeV needed (experimental tests)
- Many other models exist. See review by Petraki and Volkas '13.

Generic potential with non-renormallizable operators

$$V_{\text{eff}} = (-m^2 + AT^2)\phi^2 + \lambda\phi^4 + \gamma\phi^6 + \kappa\phi^8 + \eta\phi^{10} + ...$$

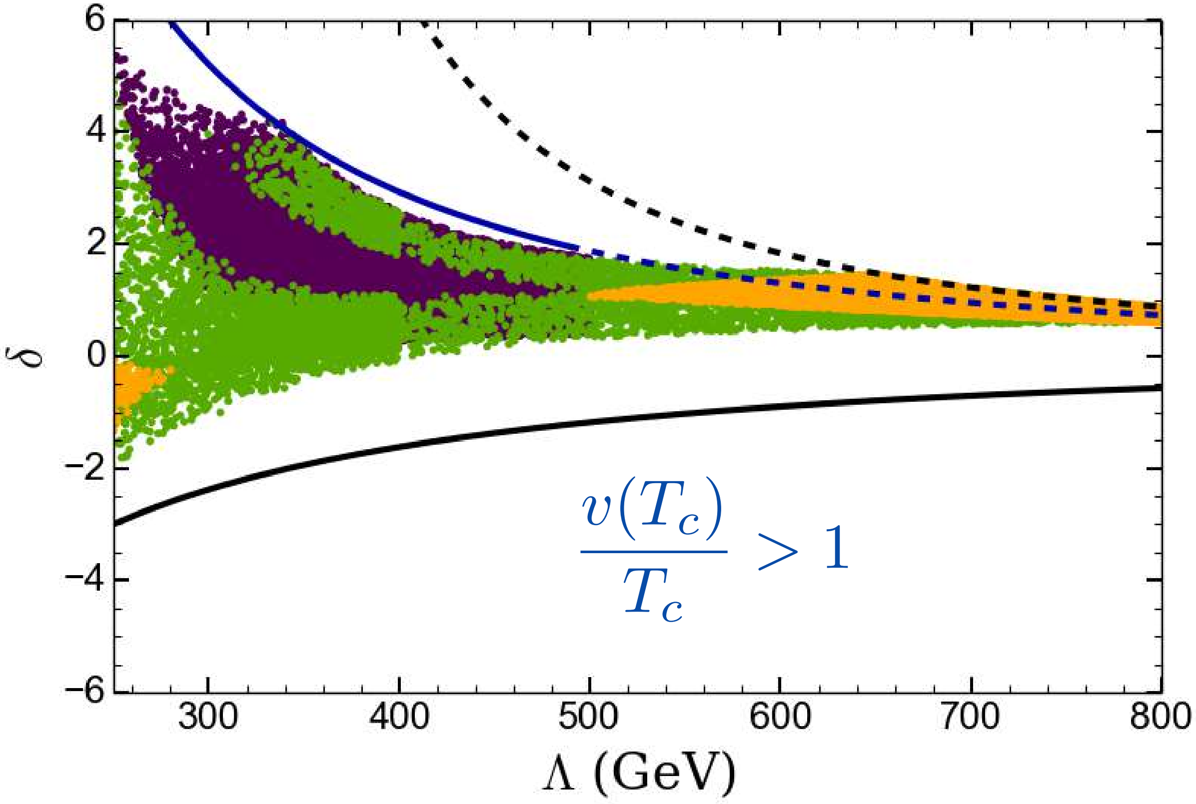
Here, $\gamma \propto 1/\Lambda^2$, $\kappa \propto 1/\Lambda^4$ and $\eta \propto 1/\Lambda^6$.

Perelstein, Grojean et al

One of the relevant characteristics of this model is that the self interactions of the Higgs are drastically modified.

Joglekar, Huang, Li, C.W.'15

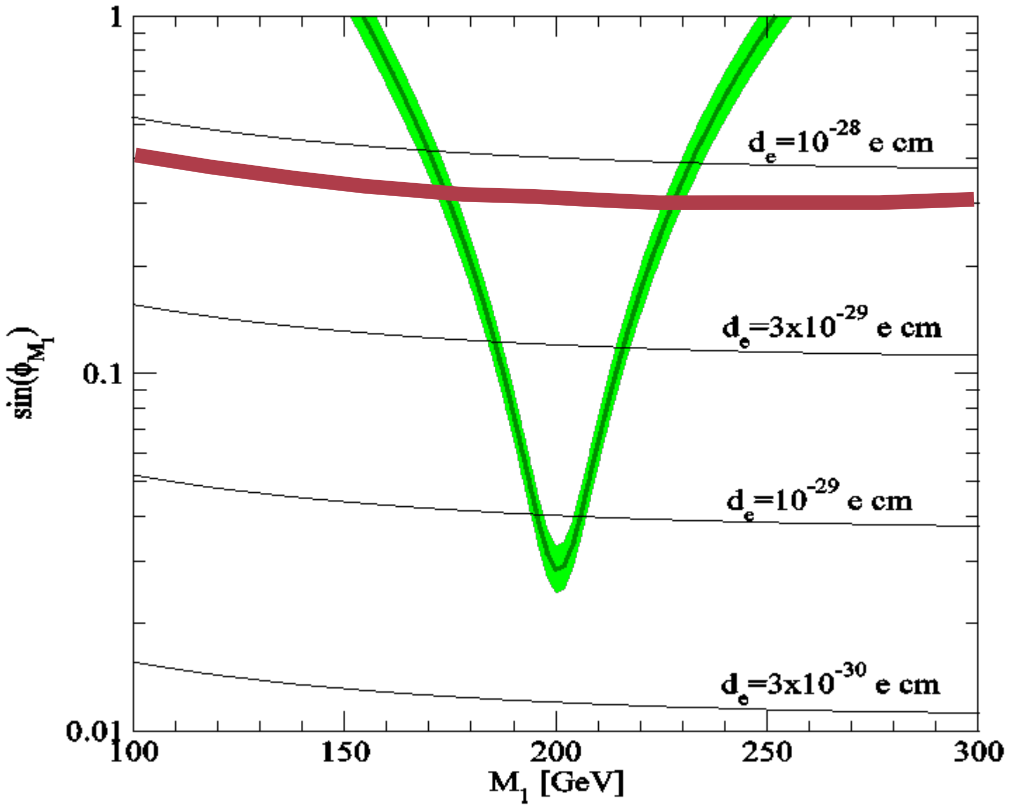
$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1$$

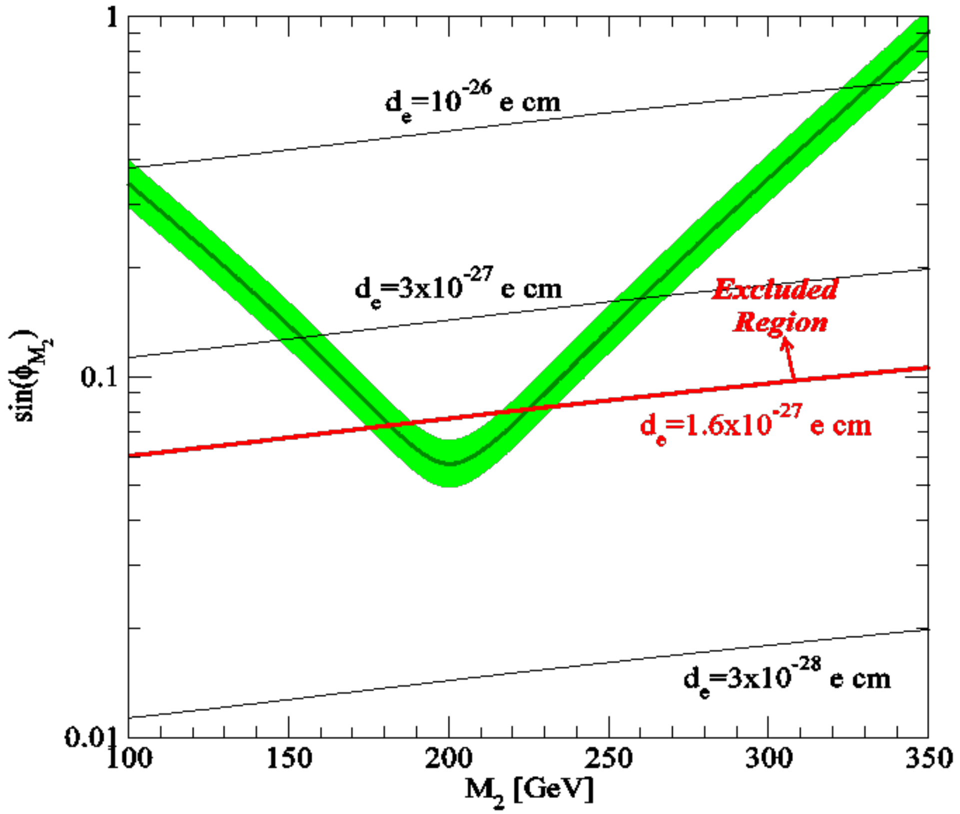


$$\frac{v(T_c)}{T_c} > 1$$

Comparing bino- and wino-driven EWB

- Electron EDM: $d_e < 8.7 \times 10^{-29}$ e cm DeMille, Doyle, Gabrielse et al'14





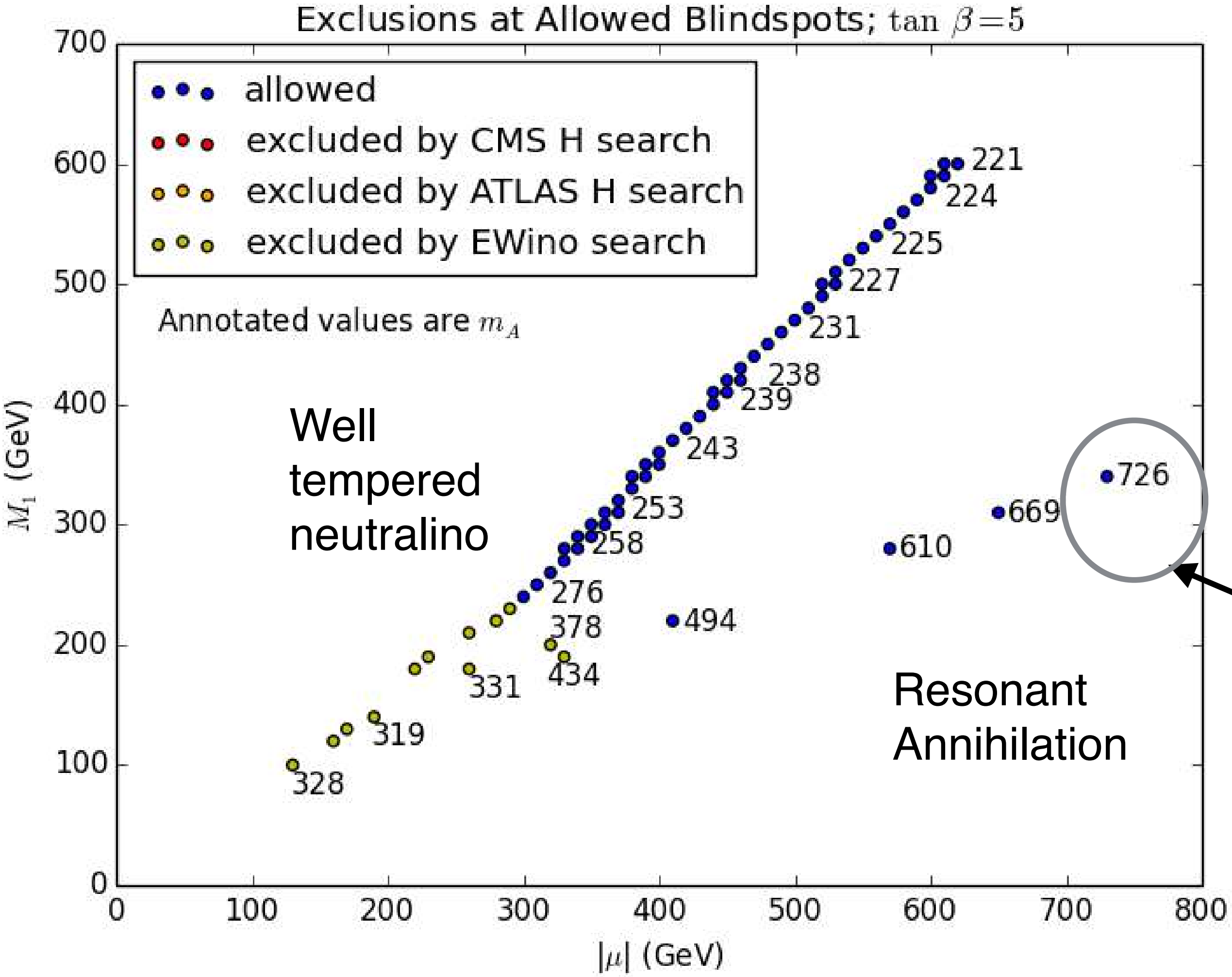
Reference Point : $|\mu| = 200\text{GeV}, \tan\beta = 10, m_{A^0} = 300\text{GeV}$

Cirigliano, Profumo, Ramsey-Musolf'06

YL, S. Profumo, M. Ramsey-Musolf, arXiv:0811.1987

Roglans, Spiegel, Sun, Huang, C.W.’16

Bounds on the Blind Spot Scenarios coming from Direct Searches for Higgs and Electroweakinos



Well tempered neutralino

Resonant Annihilation

Values of mA

Well tempered region allowed for moderate values of tanβ, but only for low values of the CP-odd Higgs mass