New Technologies for New Physics

Part I – Basics of Particle Physics

Lecture 4

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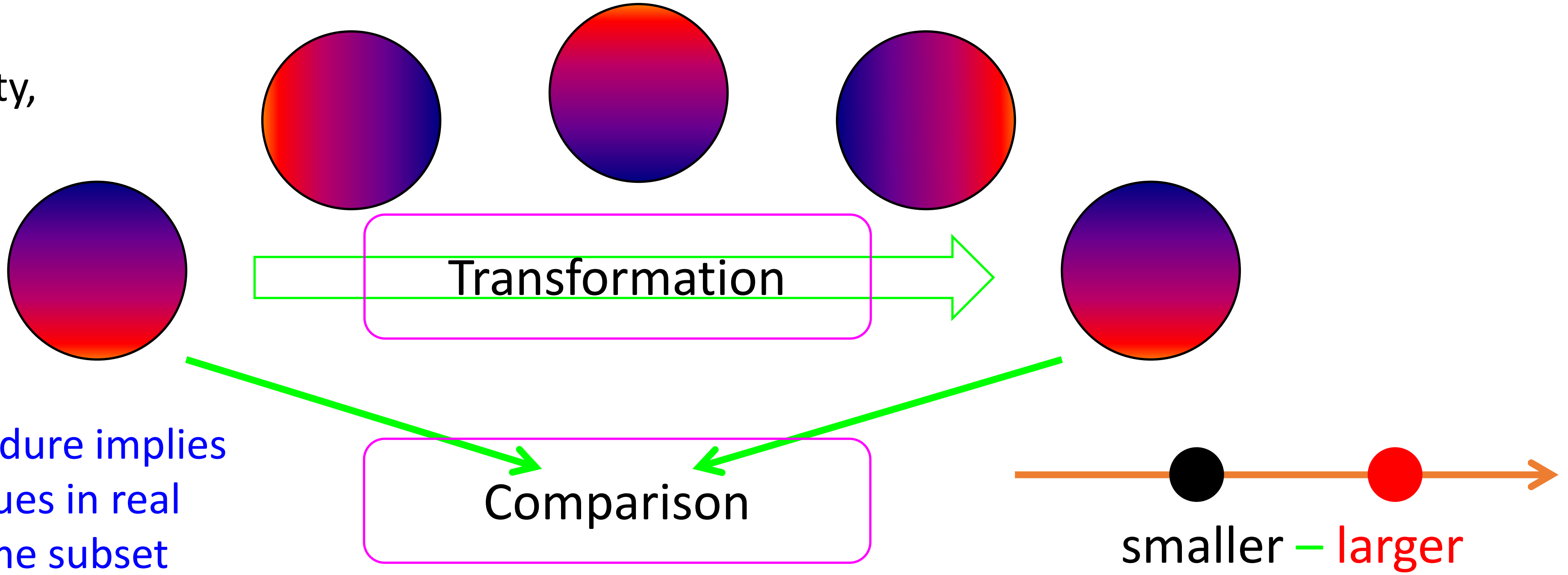
2020

- Symmetries (of the Standard Model and beyond)
- Open questions to the Standard Model
- Motivations for physics beyond the Standard Model

Symmetry

The story of symmetry in physics is about transformation and comparison

Some physical object,
or equation, or quantity,
or even process…



Transformation

Comparison

The comparison procedure implies some metrics with values in real numbers (actually, some subset with the induced topology).

smaller – larger
no – yes
worse – better
before – after
poorer – richer

Basic classification of symmetries goes along these lines:
1) what is the type of transformation (e.g. discrete or continuous) and
2) what is the metrics chosen for comparison

«It is better to be wealthy and healthy than poor and ill»

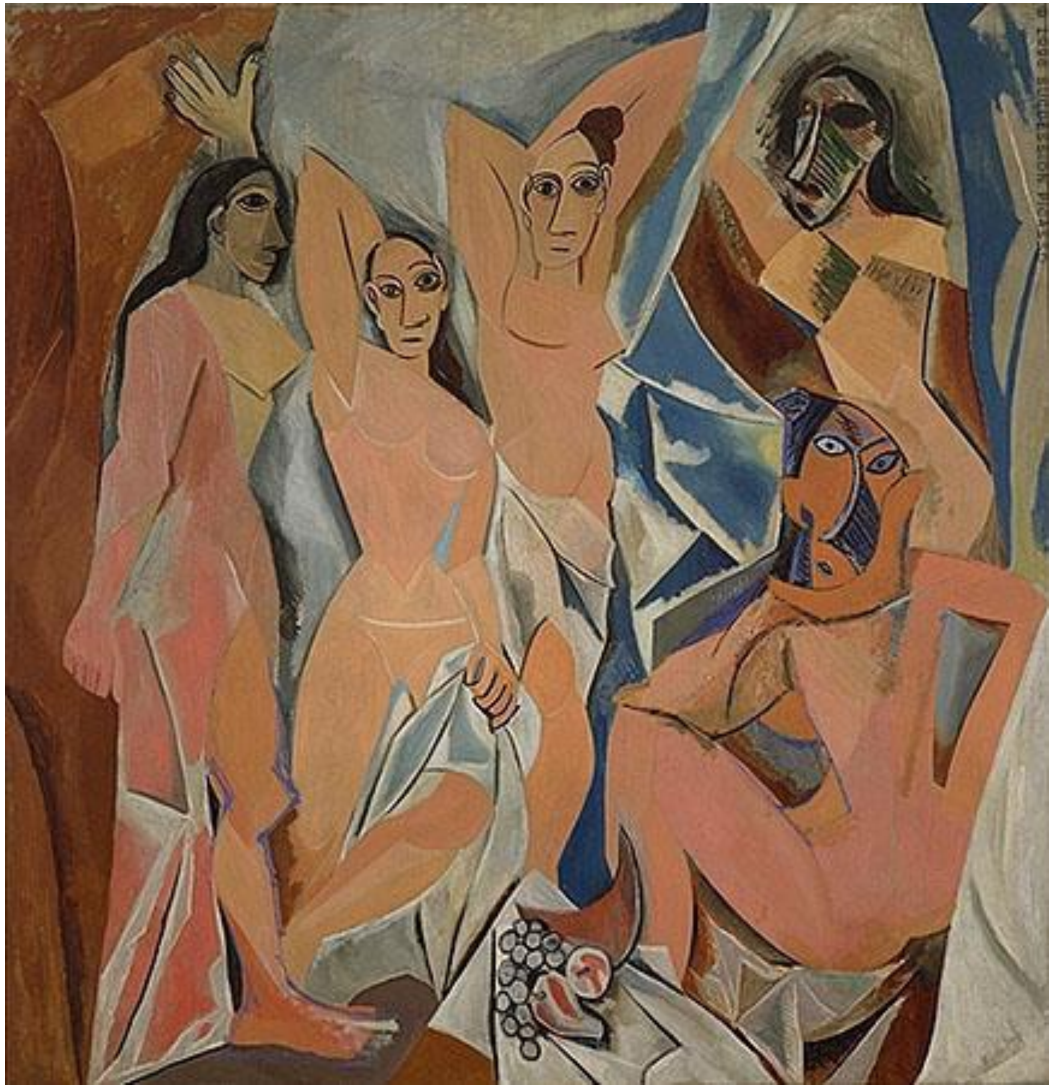
Is it better to be wealthy and ill than poor and healthy?

Maximal symmetry is usually not of much interest…

«Symmetry kills the dynamics»

Harmony ⟷ Symmetry, slightly broken

But if the symmetry violation is *too strong*, harmony is lost…



Symmetry

There are three sorts of symmetries relevant for the physics of fundamental matter properties.

- External continuous symmetries, related to coordinate transformations
- Internal symmetries, related to quantum numbers
- Discrete symmetries (charge conjugation and space-time reflections)

Moreover, the SM has many built in small/large parameters:

• Dimensionless interaction constants	$\alpha_{em}^{-1} = 137 \quad \alpha_s^{-1}(M_Z) = 8.5$
• Rank of color gauge group **SU(3)**	$1/9 = 1/3^2$
• Quark masses in strong interaction scale units	$\frac{m_{u,d}}{\Lambda} = (0.5 \div 2)\%$
• Strong to weak scales ratio	$G_F m_p^2 = 1 \cdot 10^{-5}$
• Ratios of Yukawa constants, e.g.	$\frac{m_e}{m_t} = 3 \cdot 10^{-6}$
• Quark mixing parameters	$\lambda = \lvert V_{us} \rvert = 0.22$
• …	

For almost any of them, there is a corresponding approximate symmetry of the SM which can be used for construction of the perturbation theory.

External symmetries

E.Noether
(1882 – 1935)

The fact that invariance of a system’s Lagrangian lead to some conservation law is one of the most beautiful results in theoretical physics and is known as the Noether’s theorem.

To illustrate the point, consider one degree of freedom mechanical system with the action

$$\mathcal{A} = \int_{t_a}^{t_b} dt\, L(q(t), \dot{q}(t), t)$$

Suppose the action is invariant under transformation $q(t) \to q'(t) = f(q(t), \dot{q}(t))$

or, in infinitesimal form, $\delta_{\rm s} q(t) \equiv q'(t) - q(t) = \epsilon \Delta(q(t), \dot{q}(t), t)$

$$\delta_{\rm s}\mathcal{A} = \int_{t_a}^{t_b} dt\, \cancel{\left[\frac{\partial L}{\partial q(t)} - \partial_t \frac{\partial L}{\partial \dot{q}(t)}\right]} \delta_{\rm s} q(t) + \frac{\partial L}{\partial \dot{q}(t)} \delta_{\rm s} q(t)\Big|_{t_a}^{t_b}$$

vanishes on equations of motion

So, if $\delta_{\rm s}\mathcal{A}$ vanishes, or even

$$\delta_{\rm s}\mathcal{A} = \epsilon\, \Lambda(q, \dot{q}, t)\Big|_{t_a}^{t_b}$$

since the time boundaries are arbitrary, we get for the quantity $Q(t) = \dfrac{\partial L}{\partial \dot{q}} \Delta(q, \dot{q}, t) - \Lambda(q, \dot{q}, t)$

conserved Noether charge $\dfrac{d}{dt} Q(t) = 0$

This reasoning can be generalized to many degrees of freedom, to relativistic case, to field theory etc.

For example, for complex scalar field with the Lagrangian the action is invariant under (global) field transformation $L = \frac{1}{2}(\partial_\mu\phi^*)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^*\phi$

$\phi(x) \rightarrow \phi'(x) = e^{i\alpha}\phi(x)$ the Noether current $j_\mu = i[(\partial_\mu\phi*)\phi - \phi^*(\partial_\mu\phi)]$ is conserved $\partial^\mu j_\mu = 0$

We associate this with the electric charge conservation.

Problem 1: show this!

Symmetry	Conserved quantity
Spatial rotation	Angular momentum
Temporal translation	Energy
Spatial translation	Momentum
Electromagnetic gauge invariance*	Electric charge

Comment I: the so called 1st Noether's theorem deals with global invariances. In case of local symmetries the Noether currents vanish (the 2nd Noether's theorem, see the next slide).

Comment II: neither all symmetries nor all conservation laws are Noether-like.

Internal continuous symmetries

There is another deeply nontrivial class of symmetries of the SM. These are continuous internal symmetries, i.e. symmetries, associated with local transformations of the SM fields. The best know is electromagnetic gauge symmetry.

The key idea is that different configurations of dynamical variables describe one and the same set of physical observables. Theory is local (and hence elegant and economical) in terms of non-observable potentials, while non-local (and hence cumbersome) in terms of observable field strengths).

$$\psi(x) \to \psi'(x) = e^{i\phi(x)}\psi(x) \;\Longrightarrow\; \bar{\psi}(x)(\partial_\mu - iA_\mu(x))\psi(x) \;\Longleftarrow\; A_\mu(x) \to A_\mu(x) + \partial_\mu\phi(x)$$

non-observable phase

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad L_{int} = e\int j_\mu(x)A^\mu(x)d^4x \qquad A(x) \sim \int F(z)dz$$

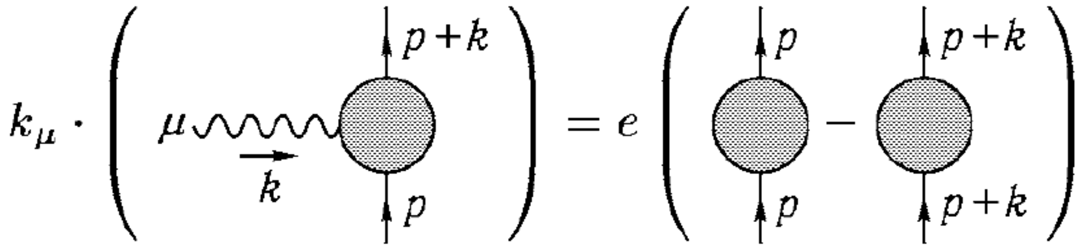
observable field

non-observable field

local interaction

nonlocal interaction

Comment III: in quantum theory, the Noether's theorem analog is known as Word-Takahashi and Slavnov-Taylor identities, which have a form of relations between quantum correlation functions.



Discrete symmetries

The crucial role in the SM is played by discreet symmetries:

- Parity **P** $\mathbf{x} \longrightarrow -\mathbf{x}$
- Time reversal **T** $t \longrightarrow -t$
- Charge conjugation **C** $e \longrightarrow -e$

Mechanical (and electromagnetic) interactions are invariant under **C**, **P**, **T** or any combination.

Physically, **CPT** theorem means that our 3+1-dimensional world made of particles is indistinguishable from the world made of antiparticles, if they move along the same worldlines backwards.

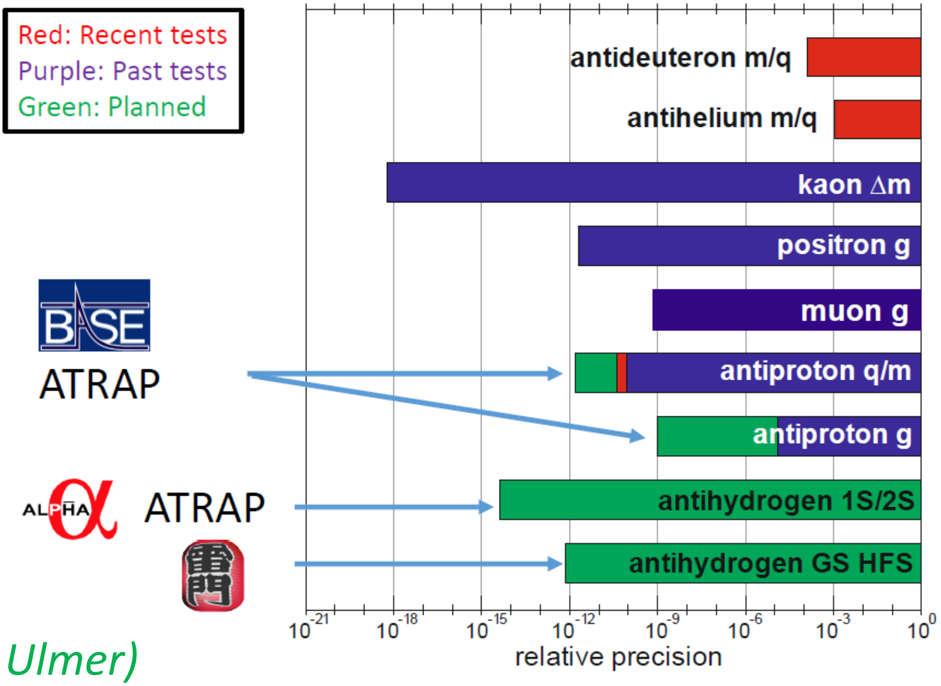
In particular, the mass of any particle must be exactly equal to the mass of its antiparticle (experimentally confirmed for K-mesons at the level 1 to 10^{18}*).*

There is an important statement known as **CPT** theorem:

Every local Lorentz-invariant field theory with Hermitian Hamiltonian is **CPT**-even.

J.Schwinger, 1951, G.Lüders, W.Pauli, 1954

Tests of CPT Invariance



(from S.Ulmer)

In the SM one can discuss discrete symmetries of interactions and internal discreet symmetries of particles.

The latter are defined for the eigenstates of discreet symmetry operator. For example, electron is not eigenstate of charge conjugation, because $\mathbf{C}|e^-\rangle = |e^+\rangle$ while photon is: $\mathbf{C}|\gamma\rangle = c|\gamma\rangle$ with $c = -1$

this choice correspond to vector nature of electromagnetic field

If interaction conserves the corresponding parity (as electromagnetic and strong interactions in the SM do), parity of the initial state must be equal to parity of the final state. This is a crude but useful tool.

Conventionally one defines intrinsic **P**-parity of the SM particles as

$$\mathbf{P}|e^-\rangle = \mathbf{P}|\nu\rangle = \mathbf{P}|q\rangle = 1 \qquad \mathbf{P}|e^+\rangle = \mathbf{P}|\bar{\nu}\rangle = \mathbf{P}|\bar{q}\rangle = -1 \qquad \mathbf{P}|\gamma\rangle = -|\gamma\rangle$$

However the statement that parities of a particle and an antiparticle are opposite is not a matter of convention. For quark-antiquark bound states such as mesons

$$\mathbf{P}_{\text{meson}} = (-1)^{L+1}$$

C-parity is defined for neutral mesons only by interchanging quark and antiquark and swapping their positions and spin:

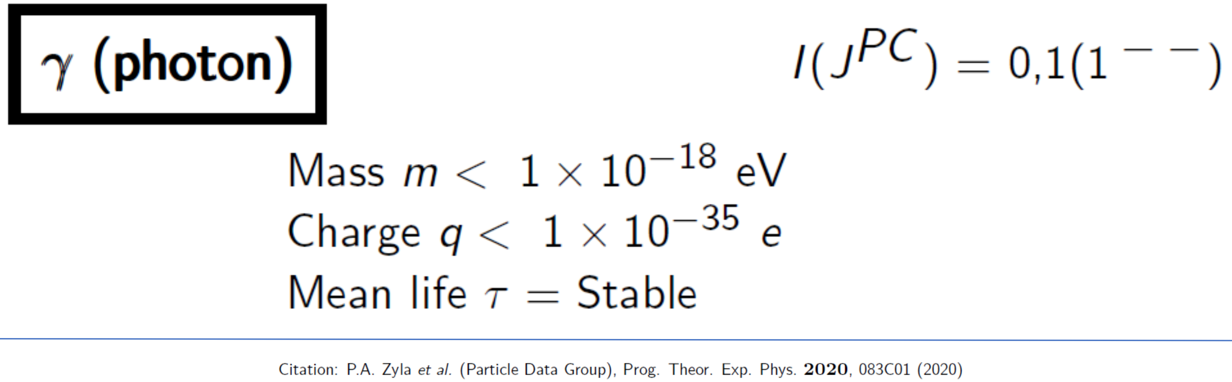
$$\mathbf{C}_{\text{meson}} = (-1)^{L+S}$$

It is convenient to mark particles by J^{PC} symbols (where **C** is to be written only for **C**-parity eigenstates).

total angular momentum

Problem 2: compare decay modes $\rho^0 \to \pi^+\pi^-$ and $\rho^0 \to \pi^0\pi^0$ from **P**- and **C**- parity conservation point of view.

Example from Particle Data Group tables



γ (photon)

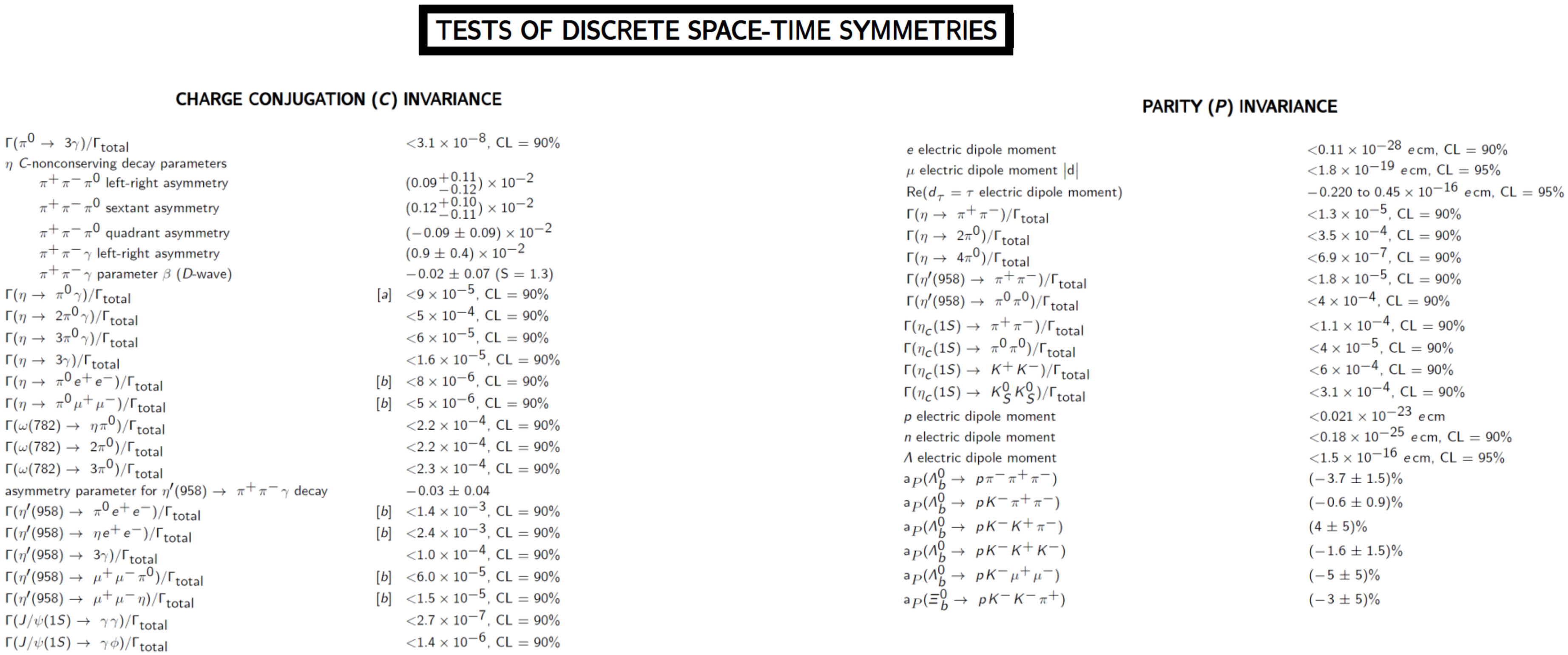
$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV

Charge $q < 1 \times 10^{-35}$ e

Mean life τ = Stable

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)



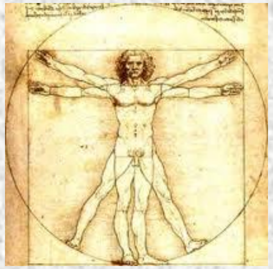
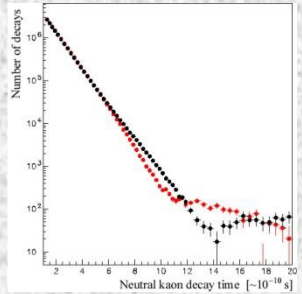
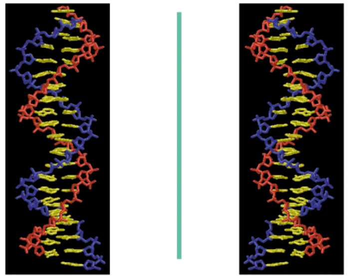
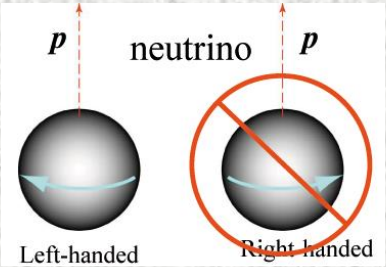
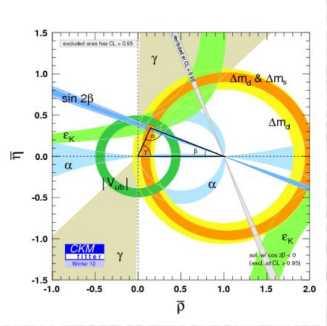
TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (*C*) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{\text{total}}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry		$(0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry		$(0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry		$(-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{\text{total}}$	[*a*]	$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0\gamma)/\Gamma_{\text{total}}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 3\pi^0\gamma)/\Gamma_{\text{total}}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{\text{total}}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[*b*]	$<8 \times 10^{-6}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	[*b*]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 2\pi^0)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{\text{total}}$		$<2.3 \times 10^{-4}$, CL = 90%
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.03 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[*b*]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{\text{total}}$	[*b*]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$	[*b*]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{\text{total}}$	[*b*]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-7}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\phi)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-6}$, CL = 90%

PARITY (*P*) INVARIANCE

e electric dipole moment	$<0.11 \times 10^{-28}$ $e\,$cm, CL = 90%
μ electric dipole moment $\lvert d \rvert$	$<1.8 \times 10^{-19}$ $e\,$cm, CL = 95%
Re($d_\tau = \tau$ electric dipole moment)	-0.220 to 0.45×10^{-16} $e\,$cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0)/\Gamma_{\text{total}}$	$<3.5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 4\pi^0)/\Gamma_{\text{total}}$	$<6.9 \times 10^{-7}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<1.8 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta_c(1S) \to K^+K^-)/\Gamma_{\text{total}}$	$<6 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to K^0_S K^0_S)/\Gamma_{\text{total}}$	$<3.1 \times 10^{-4}$, CL = 90%
p electric dipole moment	$<0.021 \times 10^{-23}$ $e\,$cm
n electric dipole moment	$<0.18 \times 10^{-25}$ $e\,$cm, CL = 90%
Λ electric dipole moment	$<1.5 \times 10^{-16}$ $e\,$cm, CL = 95%
$a_P(\Lambda^0_b \to p\pi^-\pi^+\pi^-)$	$(-3.7 \pm 1.5)\%$
$a_P(\Lambda^0_b \to pK^-\pi^+\pi^-)$	$(-0.6 \pm 0.9)\%$
$a_P(\Lambda^0_b \to pK^-K^+\pi^-)$	$(4 \pm 5)\%$
$a_P(\Lambda^0_b \to pK^-K^+K^-)$	$(-1.6 \pm 1.5)\%$
$a_P(\Lambda^0_b \to pK^-\mu^+\mu^-)$	$(-5 \pm 5)\%$
$a_P(\Xi^0_b \to pK^-K^-\pi^+)$	$(-3 \pm 5)\%$

	Macro		Micro
C		**Matter dominance**	
P		**Chirality**	
T		**Arrows of time**	

$$\begin{array}{llllll}
\textbf{P} & (A^0,\mathbf{A})_{ab} \to (-A^0,\mathbf{A})_{ab} & & (V^0,\mathbf{V})_{ab} \to (V^0,-\mathbf{V})_{ab} \\
\textbf{T} & (A^0,\mathbf{A})_{ab} \to (A^0,-\mathbf{A})_{ba} & & (V^0,\mathbf{V})_{ab} \to (V^0,-\mathbf{V})_{ba} \\
\textbf{C} & (A^0,\mathbf{A})_{ab} \to (A^0,\mathbf{A})_{ba} & & (V^0,\mathbf{V})_{ab} \to -(V^0,\mathbf{V})_{ba}
\end{array}$$

T.D.Lee, C.N.Yang, **1956**

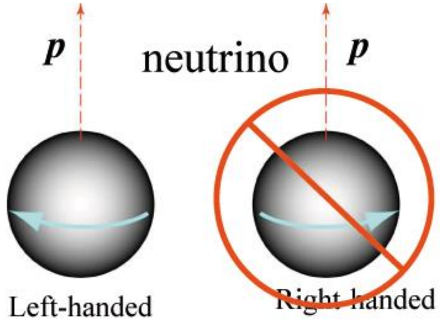
C.S.Wu, **1957**

100% **P**-parity violation is built in the SM Lagrangian

$$\Delta L = -\frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i\,\gamma^\mu\,(1-\gamma^5)(T^+\,W^+_\mu + T^-\,W^-_\mu)\,\psi_i$$

$$\bar{\psi}\gamma^\mu(1-\gamma^5)\psi = 2\bar{\psi}_L\gamma^\mu\psi_L$$

$$\psi_L = \frac{1-\gamma^5}{2}\psi \qquad \psi_R = \frac{1+\gamma^5}{2}\psi$$



$$(V-A)(V-A)^\dagger = VV^\dagger + VA^\dagger + AV^\dagger + AA^\dagger$$

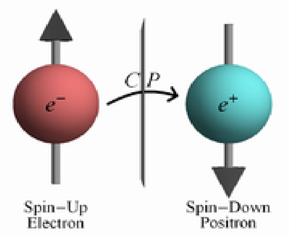
P ↓ **C** ↕

$$(V-A)(V-A)^\dagger = VV^\dagger - VA^\dagger - AV^\dagger + AA^\dagger$$

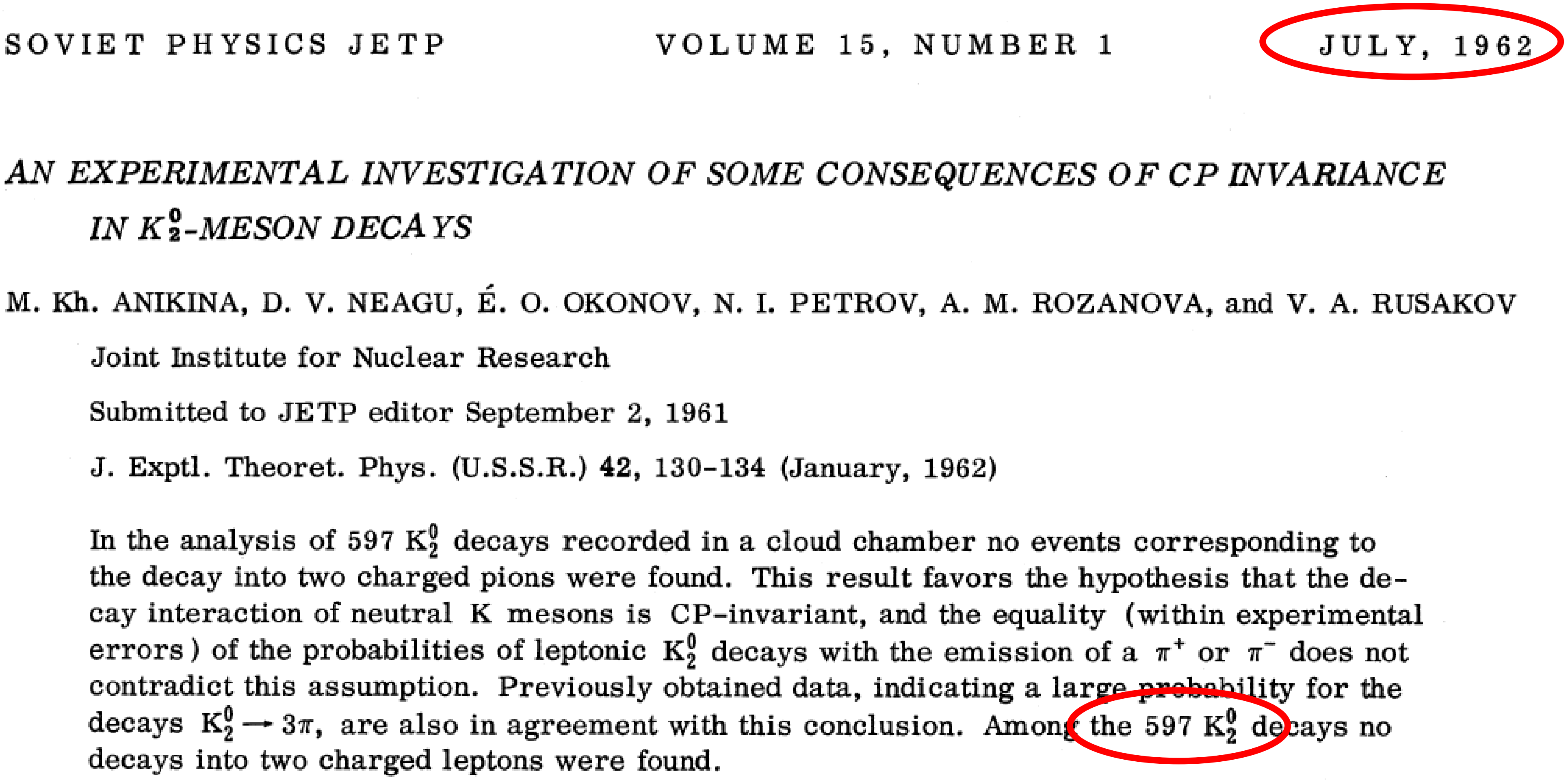
The SM Lagrangian seems to be **P**-odd but **CP**-even.

$$\begin{tikzcd}
\pi^+ \to \mu^+_R + \nu_L \arrow[r, "P"] \arrow[d, "C"] \arrow[dr, "CP"] & \pi^+ \to \mu^+_L + \cancel{\nu_R} \\
\pi^- \to \mu^-_R + \cancel{\overline{\nu}_L} & \pi^- \to \mu^-_L + \overline{\nu}_R
\end{tikzcd}$$

Combined **CP**-parity
conservation hypothesis
L.Landau, **1957**



When is it enough?



SOVIET PHYSICS JETP VOLUME 15, NUMBER 1 JULY, 1962

AN EXPERIMENTAL INVESTIGATION OF SOME CONSEQUENCES OF CP INVARIANCE IN K_2^0-MESON DECAYS

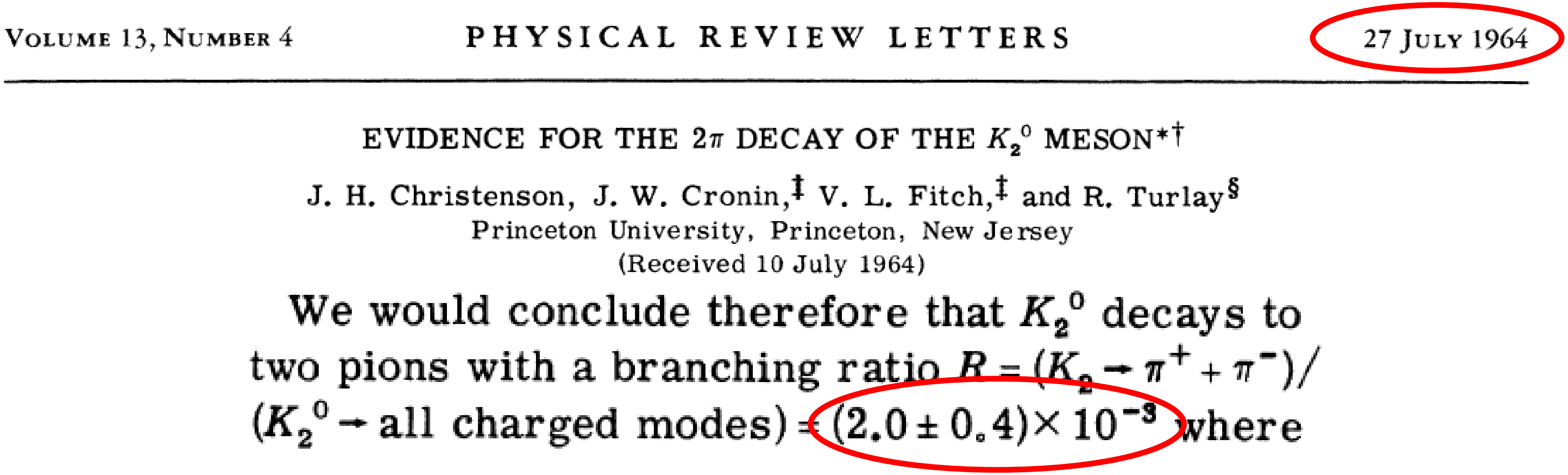
M. Kh. ANIKINA, D. V. NEAGU, É. O. OKONOV, N. I. PETROV, A. M. ROZANOVA, and V. A. RUSAKOV

Joint Institute for Nuclear Research

Submitted to JETP editor September 2, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 130-134 (January, 1962)

In the analysis of 597 K_2^0 decays recorded in a cloud chamber no events corresponding to the decay into two charged pions were found. This result favors the hypothesis that the decay interaction of neutral K mesons is CP-invariant, and the equality (within experimental errors) of the probabilities of leptonic K_2^0 decays with the emission of a π^+ or π^- does not contradict this assumption. Previously obtained data, indicating a large probability for the decays $K_2^0 \rightarrow 3\pi$, are also in agreement with this conclusion. Among the 597 K_2^0 decays no decays into two charged leptons were found.



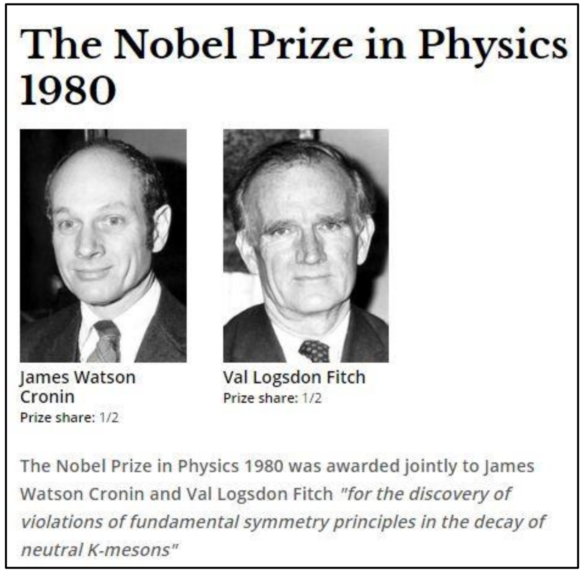
VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R=(K_2\to\pi^++\pi^-)/(K_2^0\to \text{all charged modes})=(2.0\pm0.4)\times 10^{-3}$ where



The Nobel Prize in Physics 1980

James Watson Cronin
Prize share: 1/2

Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"*

The SM mechanism for **CP** violaton was proposed by M. Kobayashi and T.Maskawa in **1974** (as a development of **1960**s work by N.Cabibbo).

M. Kobayashi

T.Maskawa

Main idea: flavour eigenstates (taking part in weak interactions) are nontrivial superpositions of mass eigenstates (solutions to the free part of the Lagrangian). In other words it is impossible to diagonalize simultaneously mass term and interaction term.

$$L_{\text{int}} = \frac{g_2}{\sqrt{2}} (\bar{u}_L,\ \bar{c}_L,\ \bar{t}_L)\gamma^\mu \hat{V}_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa matrix

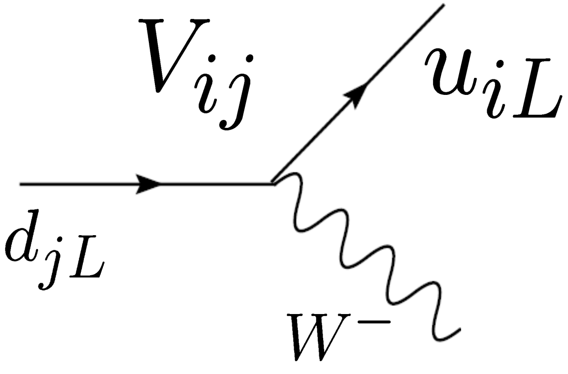
Any complex unitary N×N matrix can be parameterized by N(N-1)/2 Euler angles and (N-1)(N-2)/2 phases.

Problem 3: prove this!

So for N=2 the matrix can always be unitary rotated to equivalent pure real one.

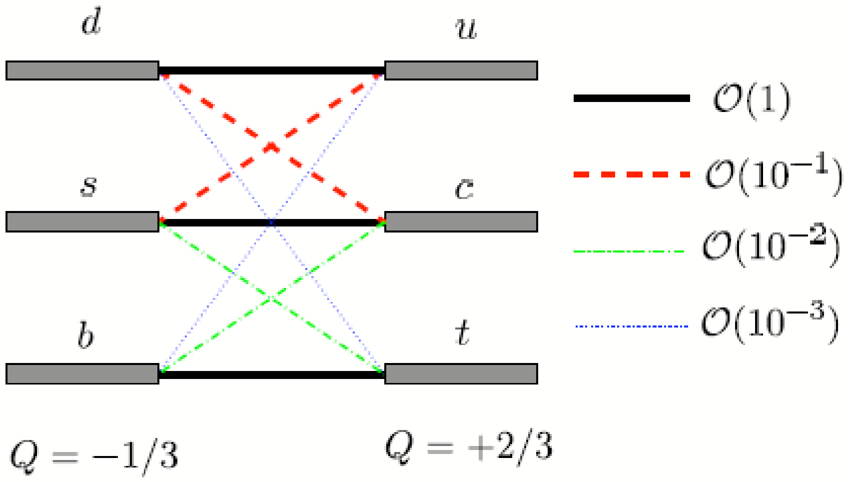
Not for N=3.

Convenient parametrization of CKM matrix implies expansion in powers of $\lambda = |V_{us}| + O(\lambda^7) = 0.2272 \pm 0.0010$

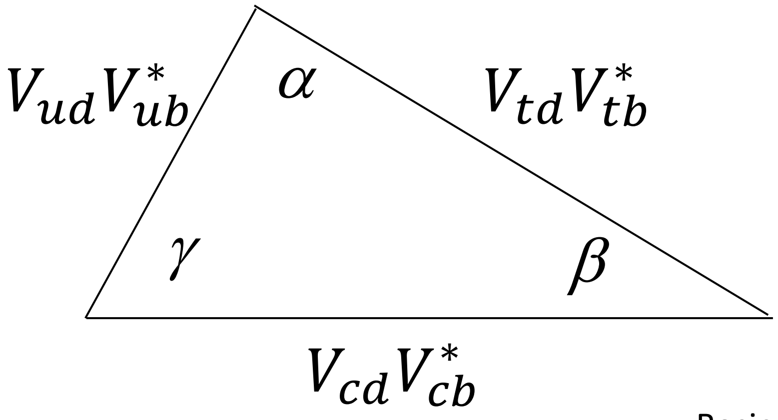


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\sim \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



6 non-diagonal unitary conditions can be represented as triangles on complex plane, the most interesting one is

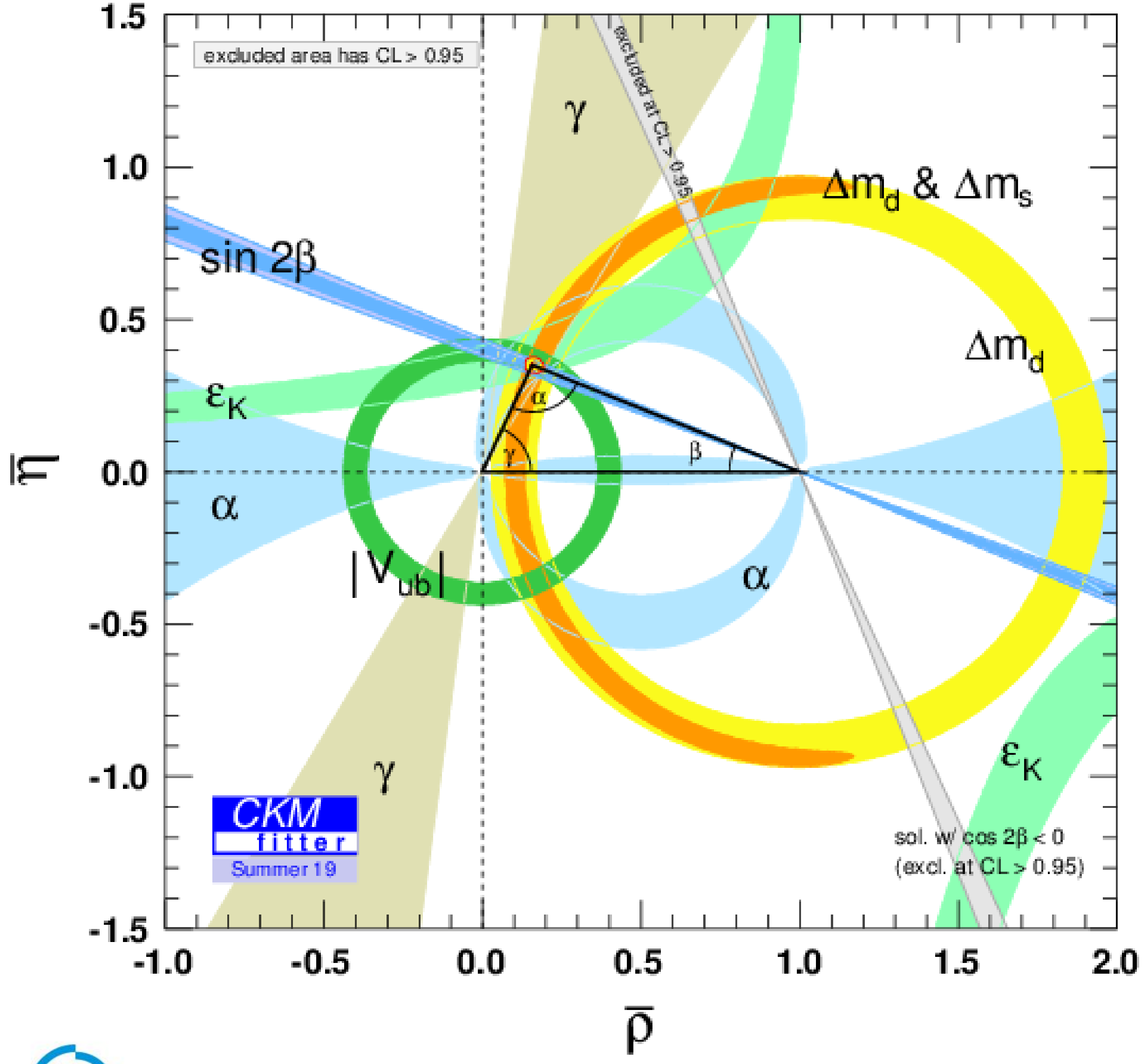


$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

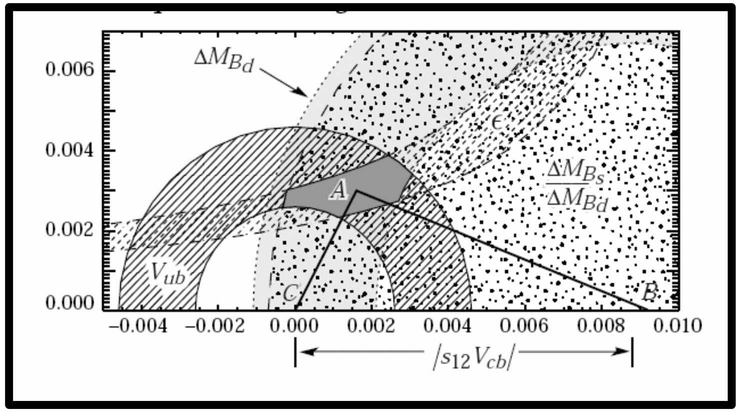
$$V_{td} = |V_{td}|e^{-i\beta}$$

$$R_b e^{i\gamma} + R_t e^{-i\beta} = 1$$

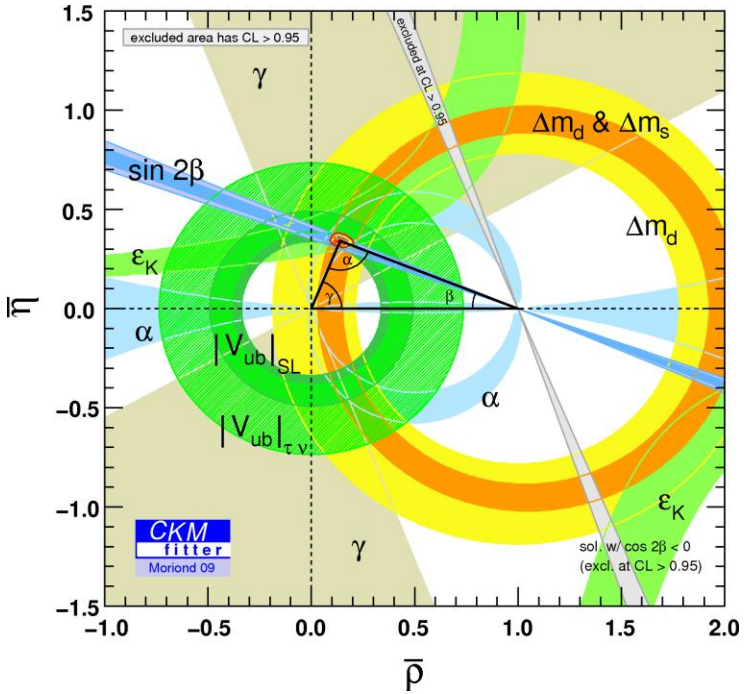
Current (2020) view of the unitarity triangle



1997:



2009:

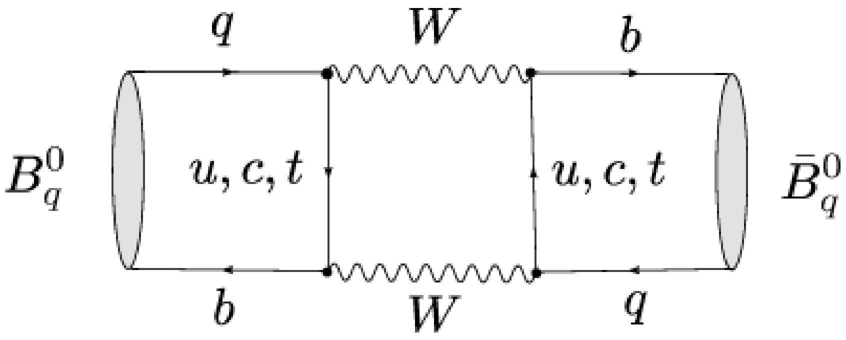


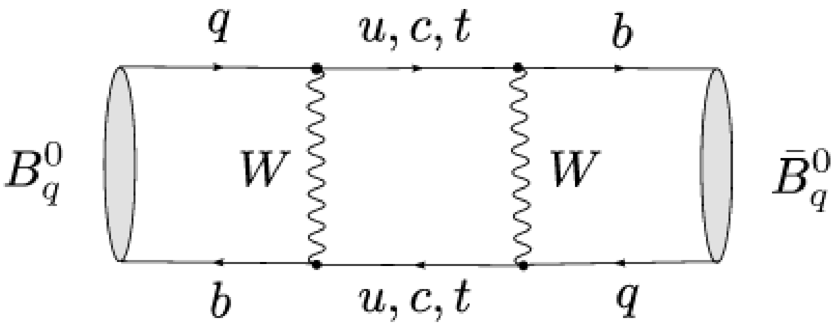
Complex phases in the couplings lead to observable CP-asymmetries

$$\mathcal{A}_{\mathrm{CP}}(t) \equiv \frac{\Gamma(B_q^0(t)\to f)-\Gamma(\bar{B}_q^0(t)\to f)}{\Gamma(B_q^0(t)\to f)+\Gamma(\bar{B}_q^0(t)\to f)}$$

$$= \left[\frac{\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_q\to f)\,\cos(\Delta M_q t)+\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_q\to f)\,\sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2)-\mathcal{A}_{\Delta\Gamma}(B_q\to f)\,\sinh(\Delta\Gamma_q t/2)}\right]$$

where $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_q\to f)\equiv\frac{1-|\xi_f^{(q)}|^2}{1+|\xi_f^{(q)}|^2},\qquad \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_q\to f)\equiv\frac{2\,\mathrm{Im}\,\xi_f^{(q)}}{1+|\xi_f^{(q)}|^2}\qquad \xi_f^{(q)}=e^{-i\Theta_{M_{12}}^{(q)}}\frac{A(\bar{B}_q^0\to f)}{A(B_q^0\to f)}$

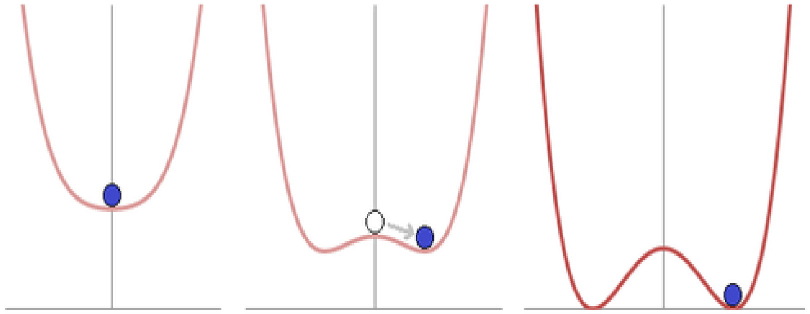


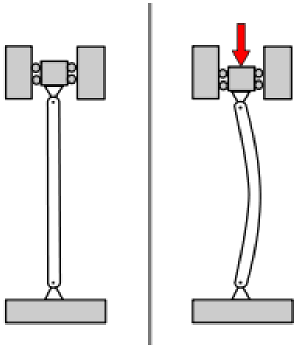


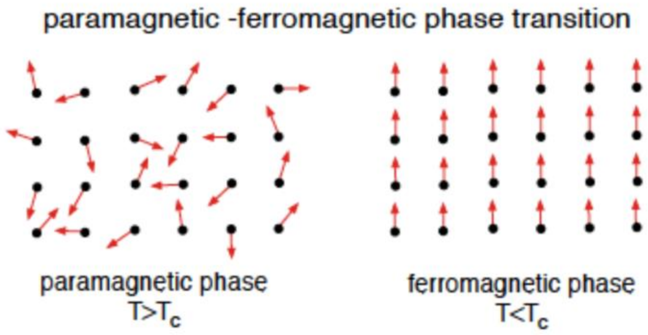
Analogous diagrams are relevant for ***K*^{0}** and ***D*^{0}** mesons oscillations

Spontaneous symmetry breaking

Symmetry of the equation may not be a symmetry of the solution to this equation, especially if it realizes extremum of some functional (for example, energy minimum).







In SM masses come from broken symmetries!

Ginzburg-Landau-Higgs mechanism

V.L.Ginzburg, L.D.Landau, 1950
P.W.Higgs, 1964; F.Englert, R.Brout, 1964
G.S.Guralnik, C.R.Hagen, T.W.Kibble, 1964

as if gauge symmetry is “broken” **$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$**

$$L = |(i\partial + A)\Phi|^2 + V(\Phi)$$

Electroweak sector of SM; superconductivity; dual Meissner scenario of confinement

Dimensional transmutation

G. ‘t Hooft, D.Gross, F.Wilczek, H.Politzer, 1973

scale invariance is broken by quantum anomaly

$$\Lambda = \mu \exp\left(-\frac{2\pi}{b\alpha_s(\mu)}\right)$$

SU(3)

Strong sector of SM, baryon masses at ~1 GeV scale

Fundamental symmetries in LHC experiments

General purpose - everything with high enough p_T

Electroweak gauge symmetry breaking pattern: Higgs boson

Space-time symmetries: extra dimensions, black holes, KK-states?

Supersymmetry: particles – superpartners? Dark matter?

Enigma of flavor

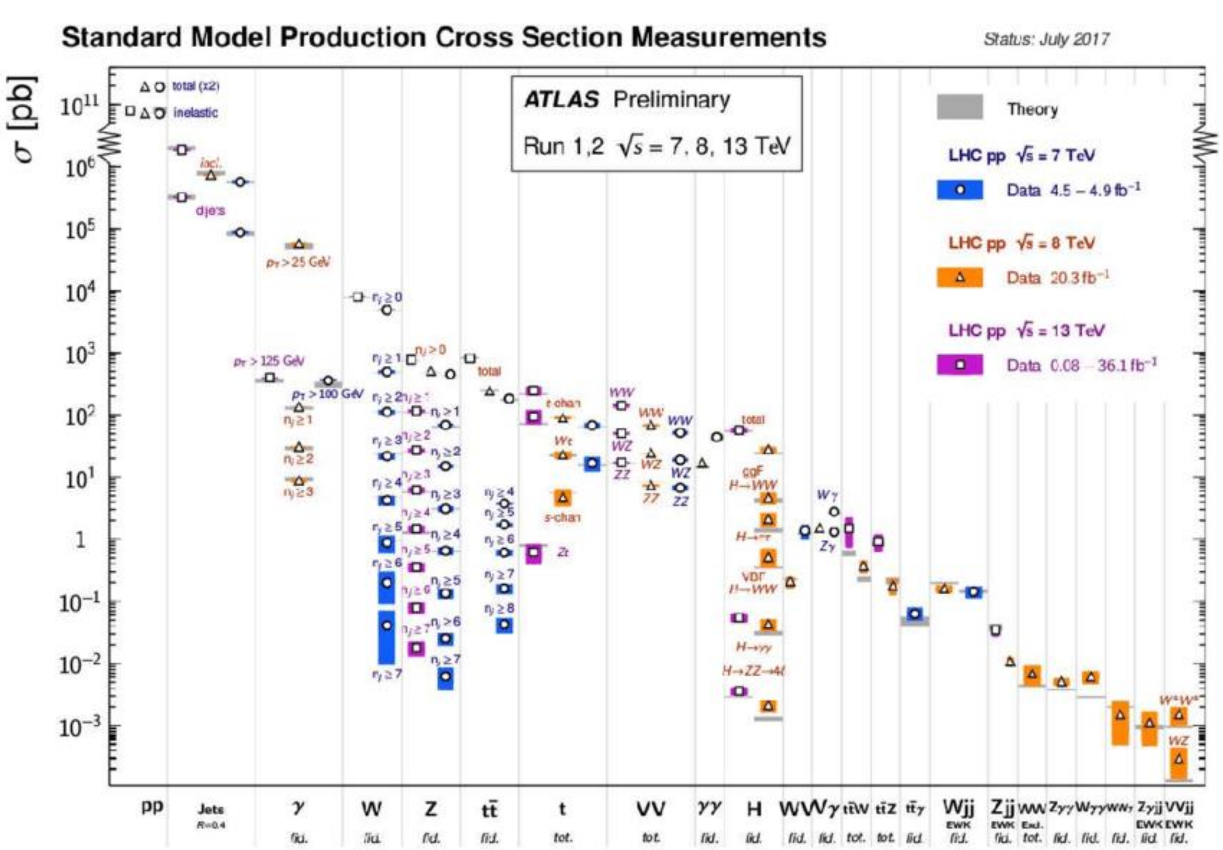
CP-symmetry violation: new sources?
Baryon asymmetry of the Universe.
Indirect search of superpartners.

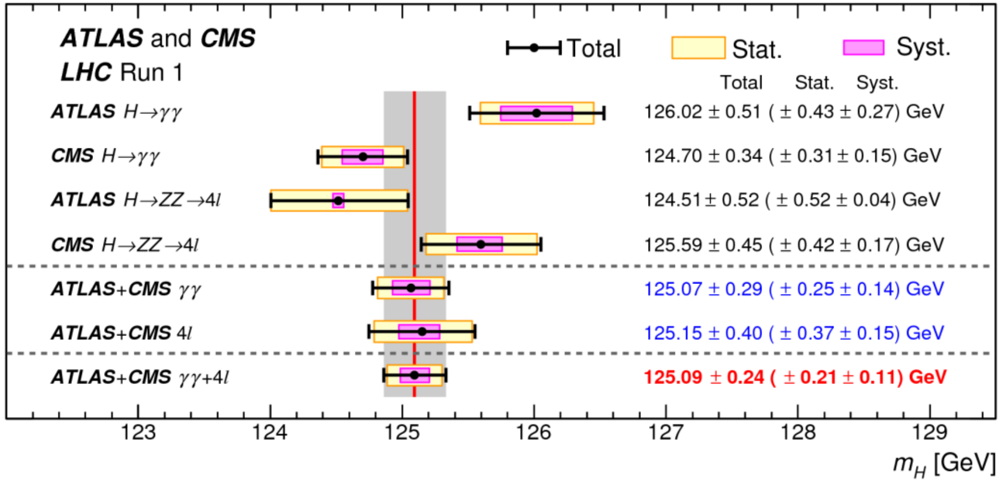
New state of matter

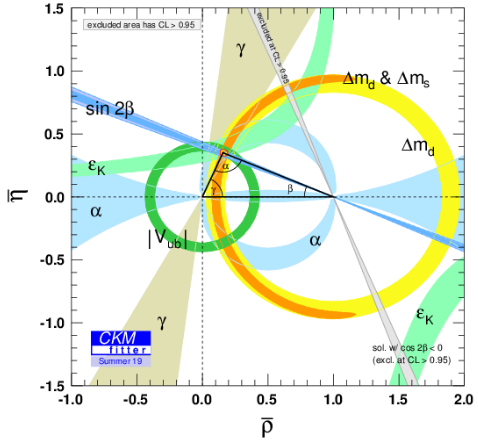
Chiral symmetry of strong interactions: pattern of restoration? Deconfinement.
P-parity violation as interplay of strong and electromagnetic interactions?

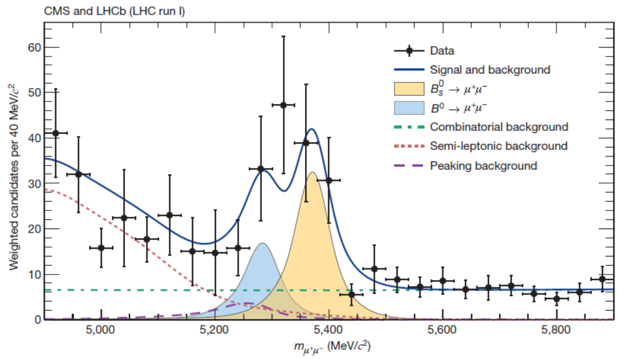
Motivations for physics beyond SM

Present status of high energy physics is characterized by undisputable triumph of the Standard Model. We have found Higgs boson, confirmed subtle predictions in electroweak and flavour physics, reached percent level accuracy in strong interaction physics…



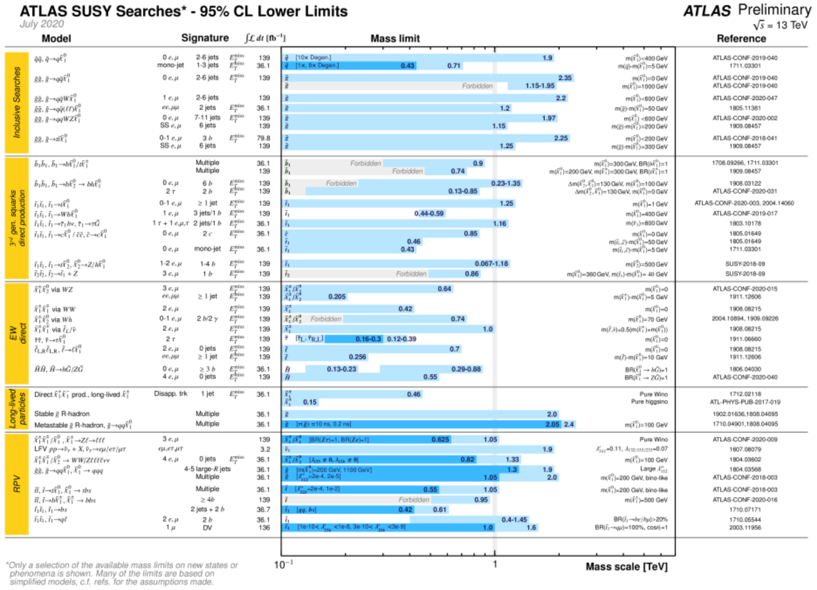


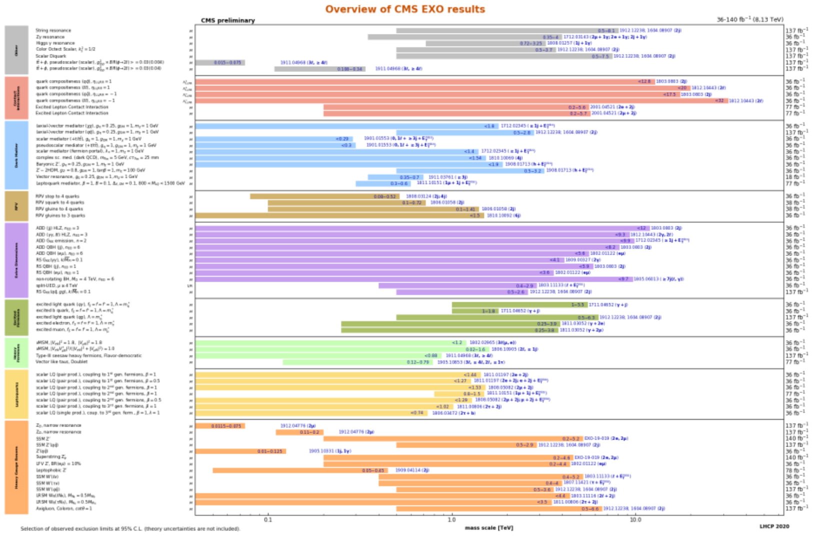


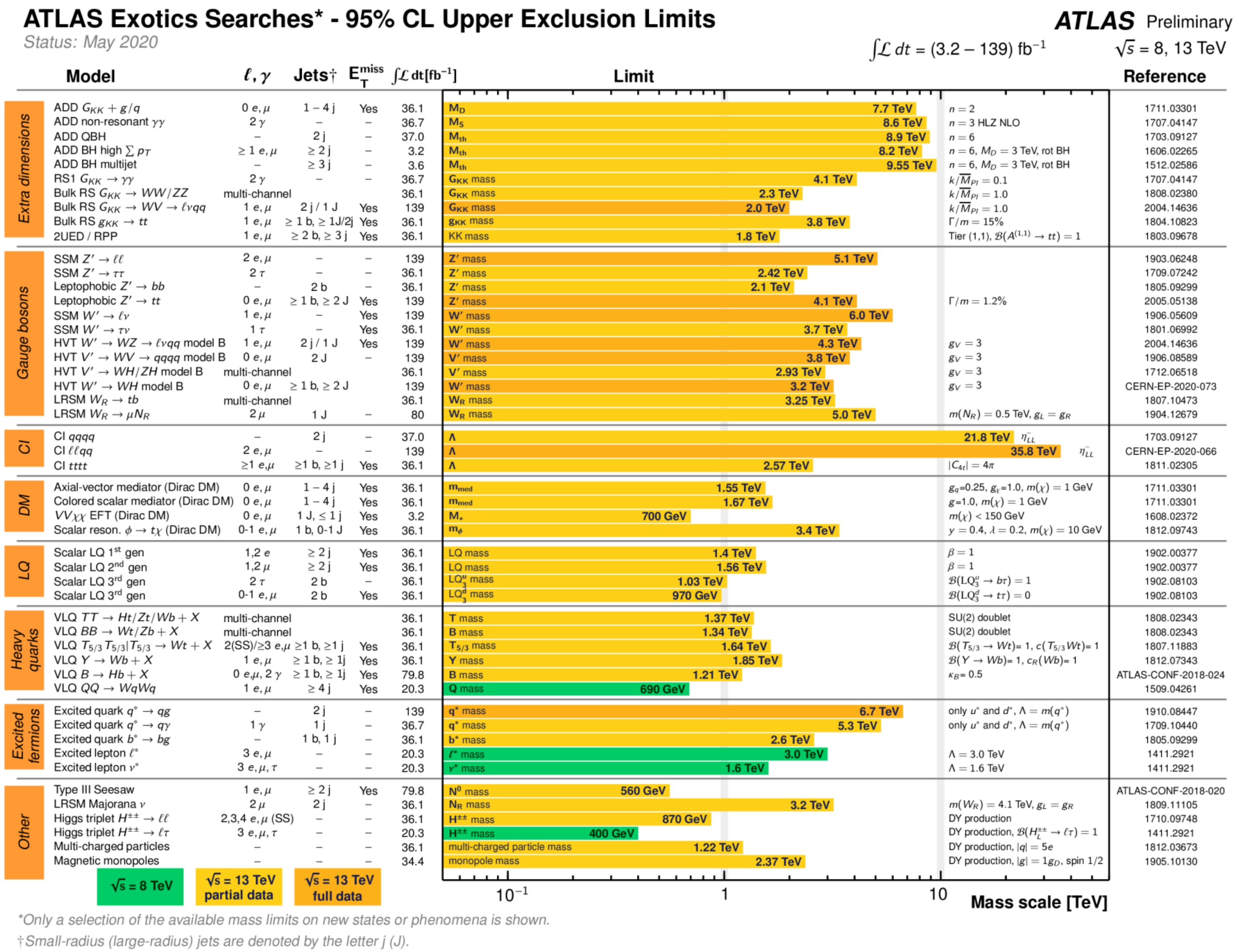


…but no signals for New Physics!

“cemetery of theories”







ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 139)$ fb^{-1}

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^{-}	CERN-EP-2020-066
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

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

†Small-radius (large-radius) jets are denoted by the letter j (J).

Why do we think that there is physics beyond the SM?

There are two lines of argument:

1. Experimental facts which cannot be explained in SM framework, among them:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

2. There are many «why» and «how» in the SM:

- What is the ultimate ultraviolet scale? If it is the Planck scale **~10^{19} GeV**, how is electroweak scale so much smaller than UV scale?
- Why do masses and couplings in SM have the values they have?
- Why are lefts doublets and rights singlets?
- Why 3 generations? Why CKM hierarchy & CP?
- What about gravity?
- ...

So, SM is definitely not a closed theory. But is it a consistent theory?

Generally speaking, NO ➡

- Landau pole
- Anomalies
- Naturalness
- …

but the things are arranged in such a tricky way in the SM, that (almost) all is cured…

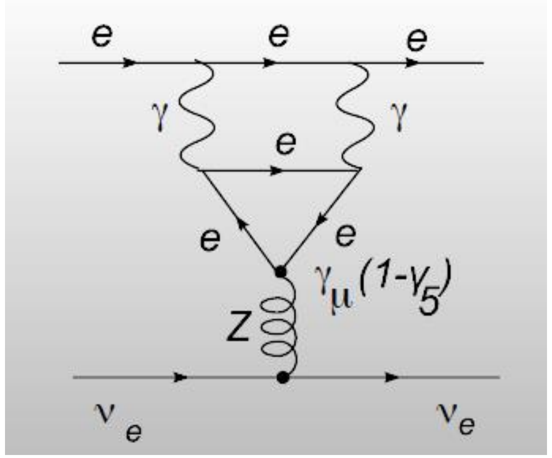
Example I: Landau pole. Quantum electrodynamics is not consistent at ultra-high energies. However, numerically, this scale $\Lambda = m_e \exp(1/b\alpha)$ is far beyond reach since

$$\alpha = \frac{1}{137}$$

Problem 4: estimate it.

Example II: cancellation of anomalies. There are dangerous divergencies in the SM which cannot be renormalized and should just cancel for consistency of the theory. They do indeed, in quite nontrivial way.

$$TrY^3 = \;=\; \underset{\substack{\uparrow\\ colour}}{3}\left[\underset{\substack{\uparrow\\ u_L}}{(\frac{1}{3})^3} + \underset{\substack{\uparrow\\ d_L}}{(\frac{1}{3})^3} - \underset{\substack{\uparrow\\ u_R}}{(\frac{4}{3})^3} - \underset{\substack{\uparrow\\ d_R}}{(-\frac{2}{3})^3}\right] + \underset{\substack{\uparrow\\ \nu_L}}{(-1)^3} + \underset{\substack{\uparrow\\ e_L}}{(-1)^3} - \underset{\substack{\uparrow\\ e_R.}}{(-2)^3} = 0$$



Links quarks and leptons!

Example III: Naturalness

Imagine you have built a 4-parameter physical model of some class of phenomena. Fitting this model to experimental observables, you found the following values for these 4 parameters (A, B, C, D):

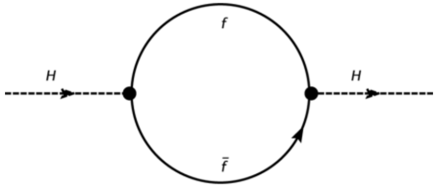
A = 1.4 **B = 0.7** **C = 2.6** **D = 3×10^{28}**

In modern science such models are known as unnatural, or fine-tuned. One may expect that physically relevant is not the parameter **D**, which is so strongly outside the ballpark of the other three ones, but some other parameter, perhaps hiding **D** inside it.

If one thinks of the SM as some effective theory valid at scales smaller than UV cutoff, then experiments indicate that $\Lambda_{UV} \gg m_{weak}$

$$\mathcal{L}_{SM} = \mathcal{L}^{d\leq4} + \frac{1}{\Lambda_{UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{d=6} + \dots$$

At the same time, naturalness suggests



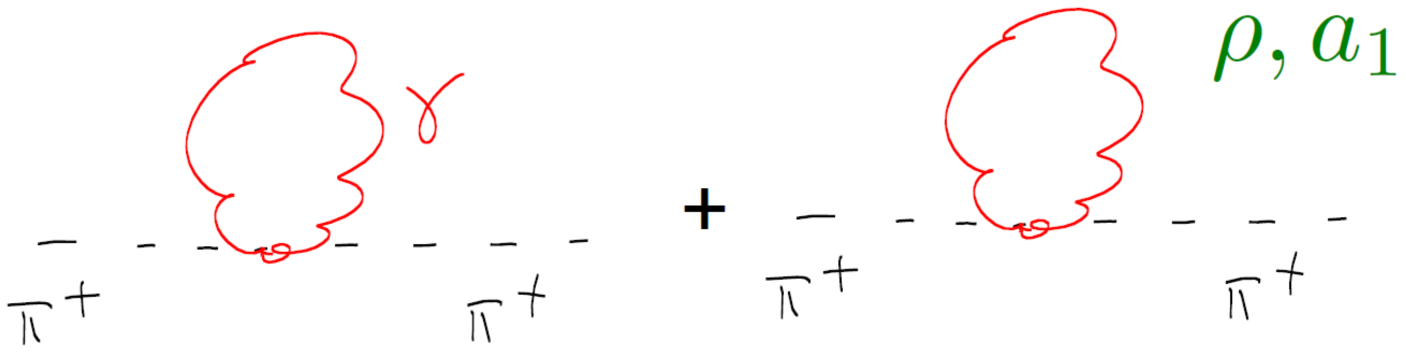
$$\sim \delta m_h^2 \sim \frac{y_t^2}{4\pi^2}\Lambda_{UV}^2 + \dots$$

Quantum instability of the Higgs mass

$$\Lambda_{UV} \lesssim 500\,\text{GeV}$$

This was the main theoretical motivation for searches of supersymmetry, since there is no quadratic divergence in quantum corrections to the Higgs mass is supersymmetric extension of SM.

Naturalness of the pion mass:



$$\delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi}\Lambda^2 \lesssim (m^2_{\pi^+} - m^2_{\pi^0})_{\rm exp} \qquad (m^2_{\pi^+} - m^2_{\pi^0})_{\rm exp} = (4\,{\rm MeV})^2$$

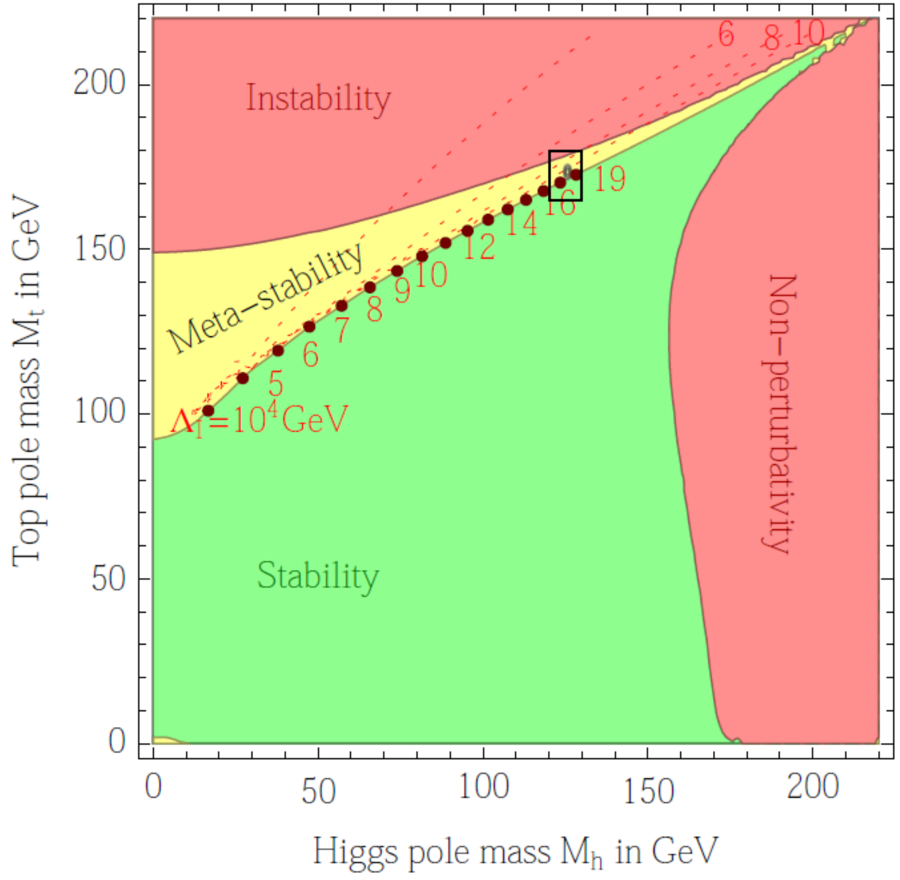
$$\Lambda \lesssim 850\ {\rm MeV}$$

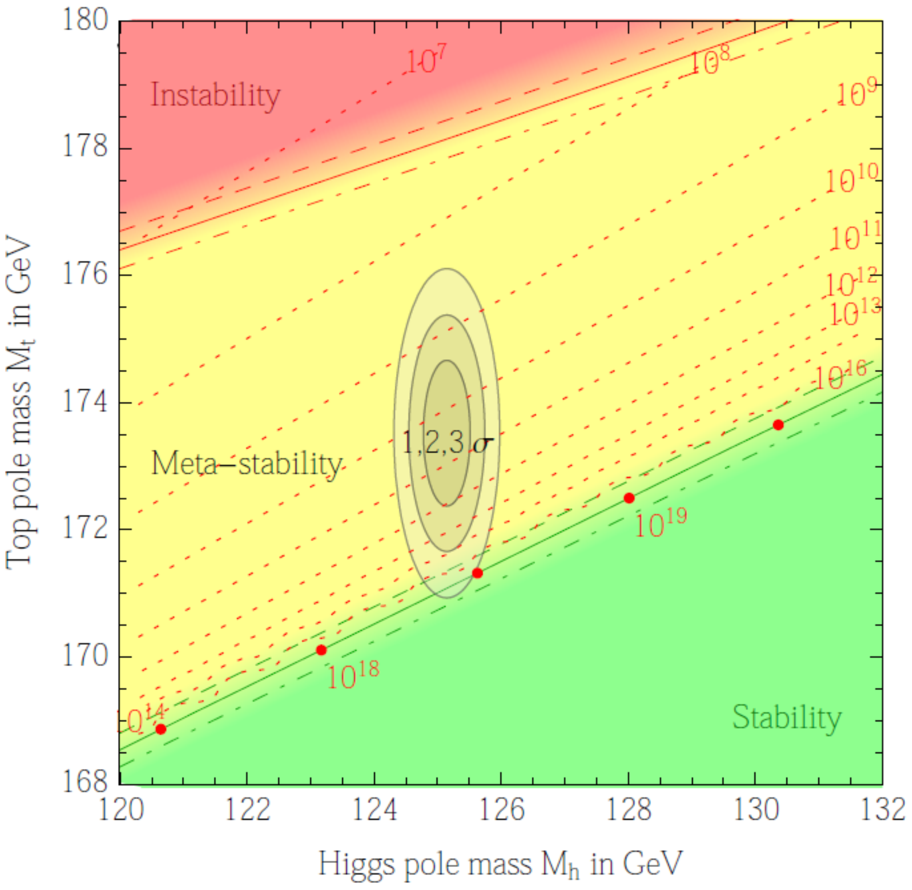
«New physics» indeed comes at $m_\rho = 770\,{\rm MeV}$

$$m^2_{\pi^+} - m^2_{\pi^0} = \frac{3\alpha}{4\pi}\frac{m^2_\rho m^2_{a_1}}{m^2_{a_1} - m^2_\rho}\log\left(\frac{m^2_{a_1}}{m^2_\rho}\right)$$

(A.Das, ‘67)

Observable Higgs mass corresponds to metastability of the SM vacuum

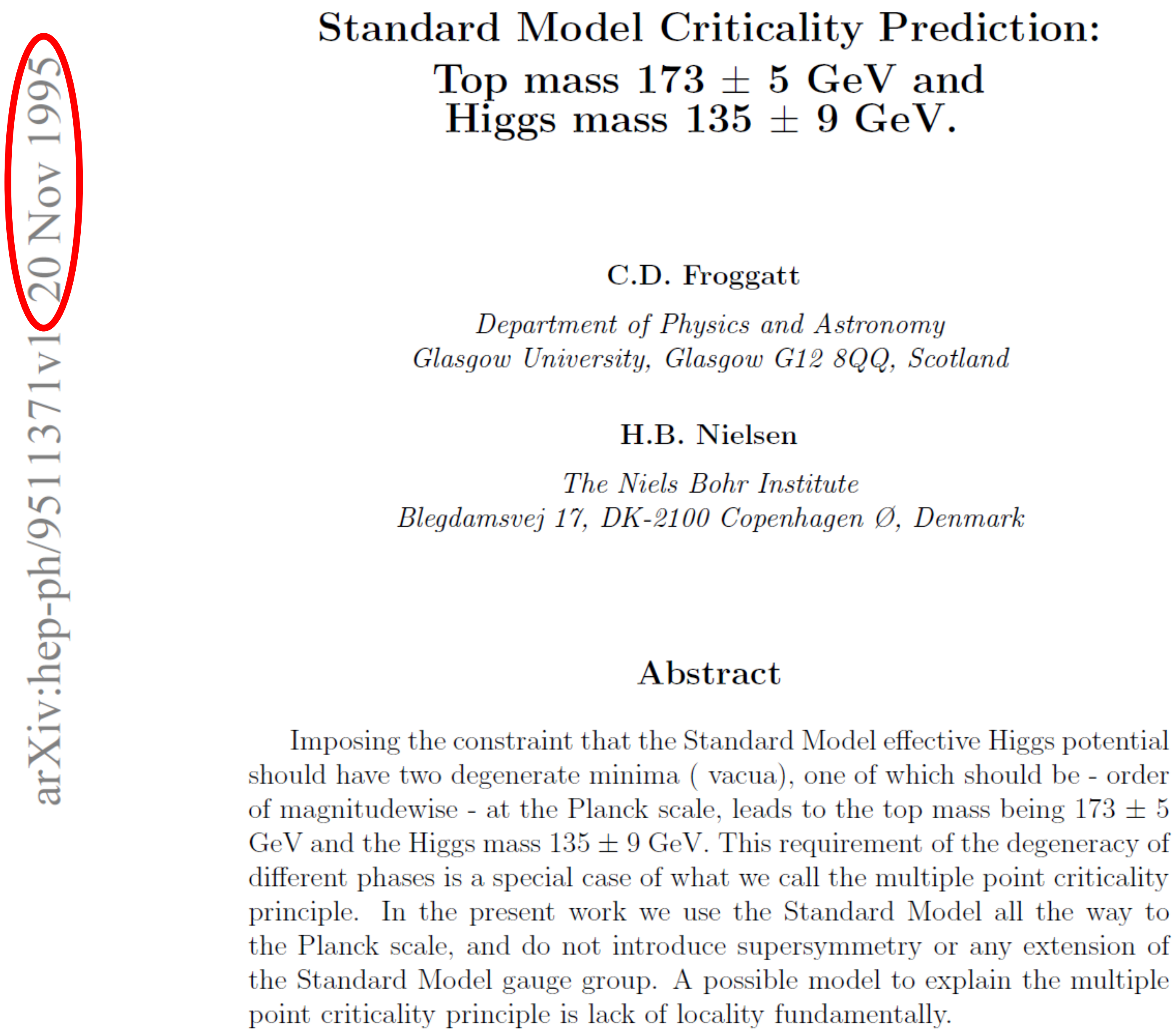




(I. V. Krive, A. D. Linde, N. Cabibbo, L. Maiani, G. Parisi, R. Petronzio, M.Lindner, H.B.Nielsen, C.Froggatt, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, A. Strumia, J. R. Espinosa, M. Quiros, G.Altarelli and many others)

(from arXiv:1307.3536)

Coincidence? Don't think so…



arXiv:hep-ph/9511371v1 20 Nov 1995

Standard Model Criticality Prediction: Top mass 173 ± 5 GeV and Higgs mass 135 ± 9 GeV.

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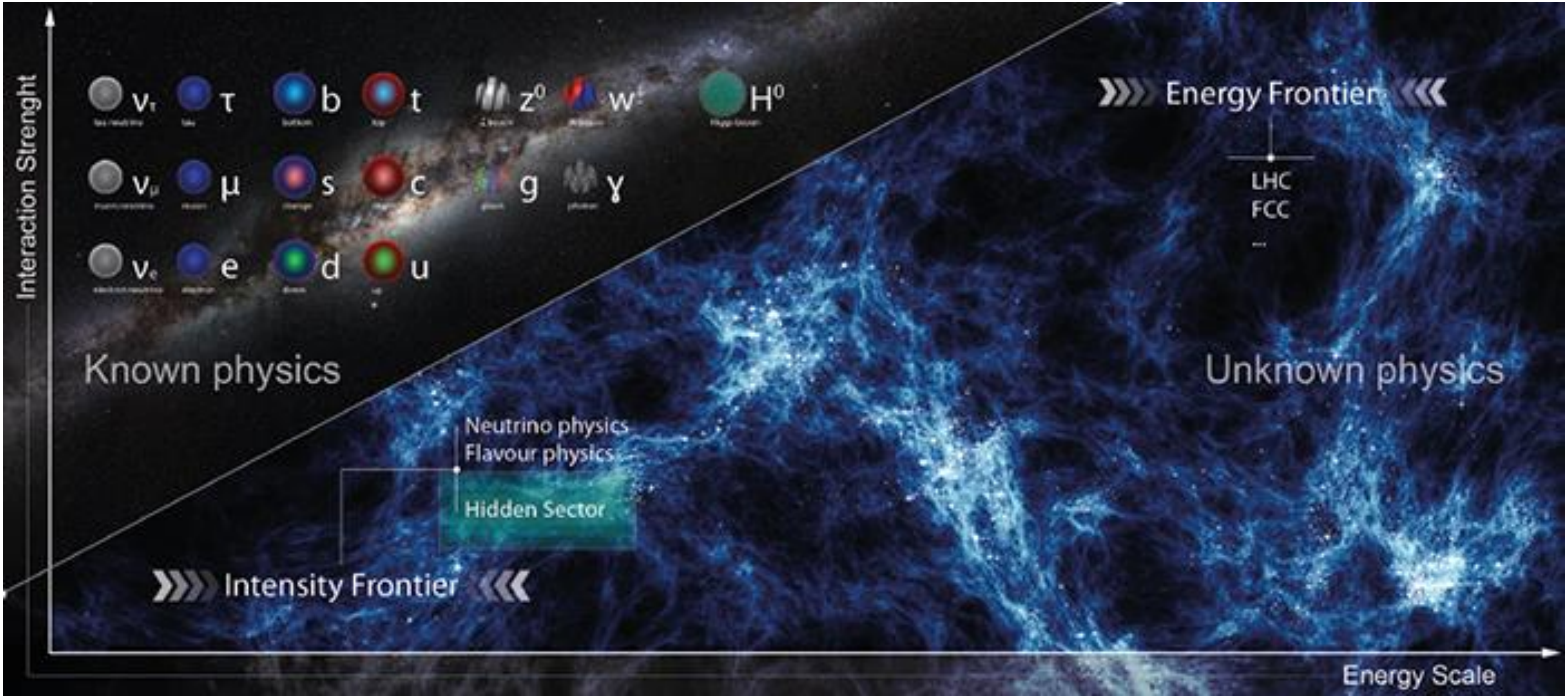
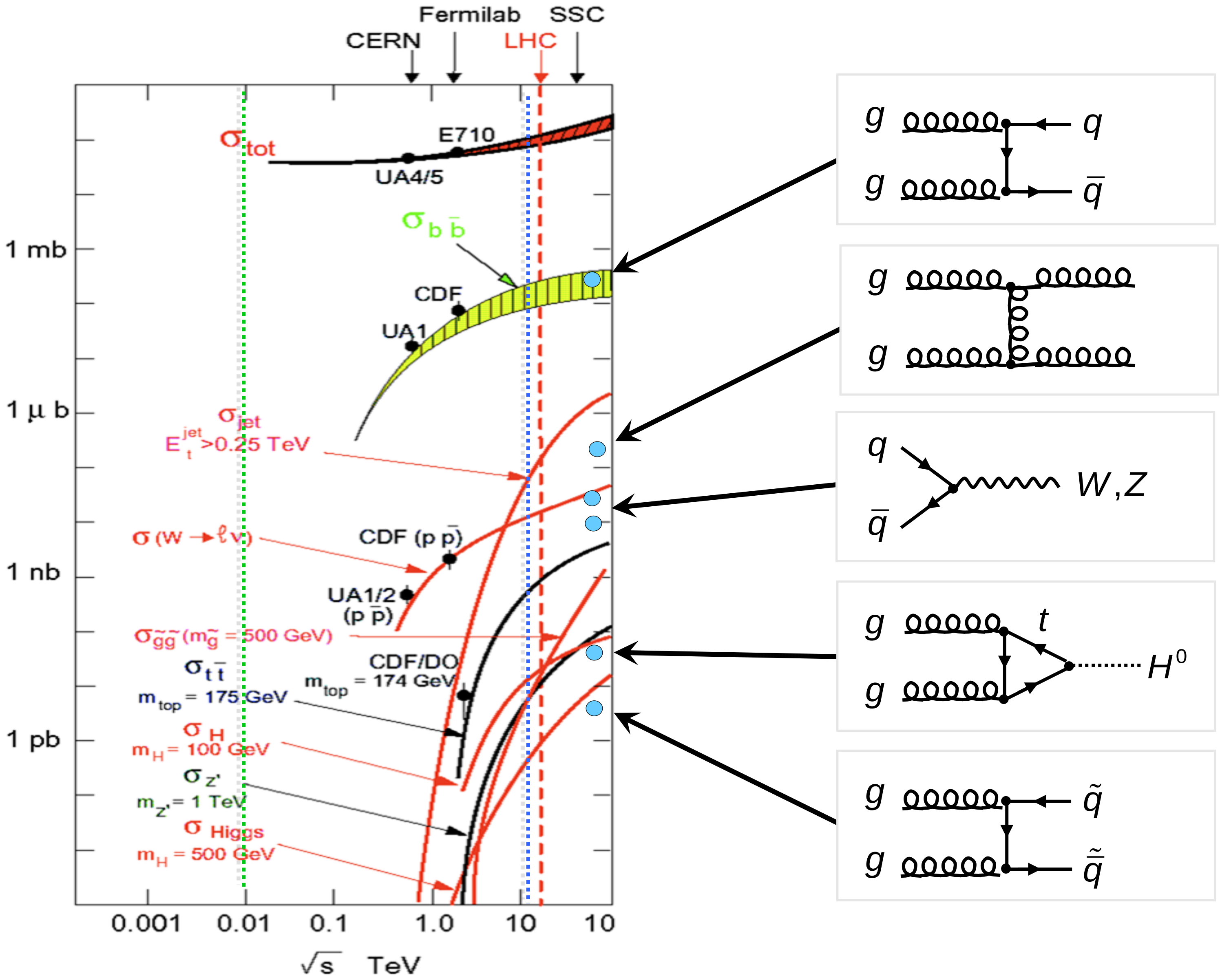
Abstract

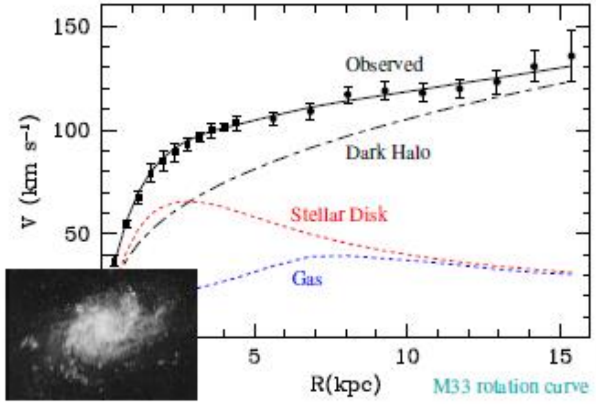
Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima (vacua), one of which should be - order of magnitudewise - at the Planck scale, leads to the top mass being 173 ± 5 GeV and the Higgs mass 135 ± 9 GeV. This requirement of the degeneracy of different phases is a special case of what we call the multiple point criticality principle. In the present work we use the Standard Model all the way to the Planck scale, and do not introduce supersymmetry or any extension of the Standard Model gauge group. A possible model to explain the multiple point criticality principle is lack of locality fundamentally.

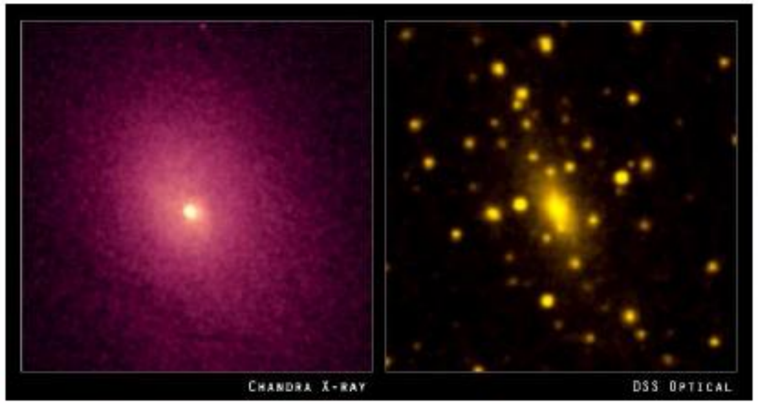

Interaction Strenght
ν_τ
τ
b
t
Z^0
$W^\pm$
H^0
ν_μ
μ
s
c
g
γ
ν_e
e
d
u
Known physics
Energy Frontier
LHC
FCC
...
Unknown physics
Neutrino physics
Flavour physics
Hidden Sector
Intensity Frontier
Energy Scale

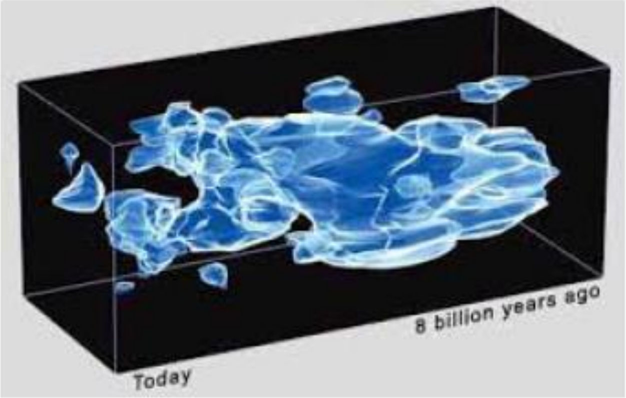
Why the energy is so important



Astrophysical evidences for dark matter…



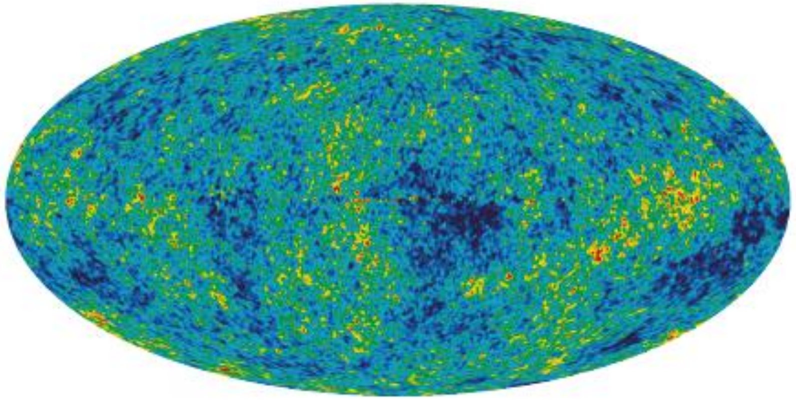




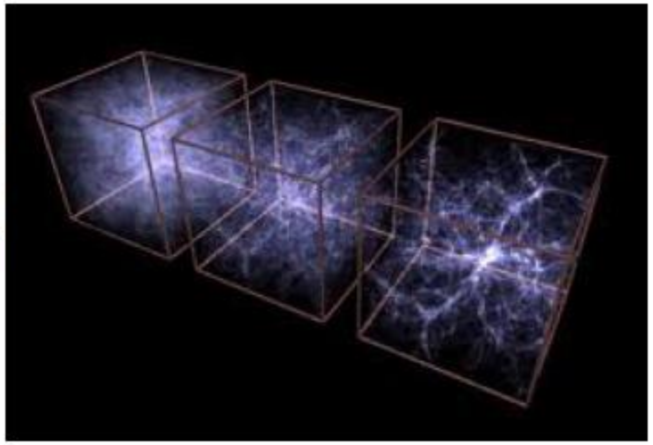
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \mathrm{const}$

Expected:
$\mathrm{mass}_{\mathrm{cluster}} = \sum \mathrm{mass}_{\mathrm{galaxies}}$
Observed: 10^2 times more mass confining ionized gas

Lensing signal (direct mass measurement) **confirms** other observations

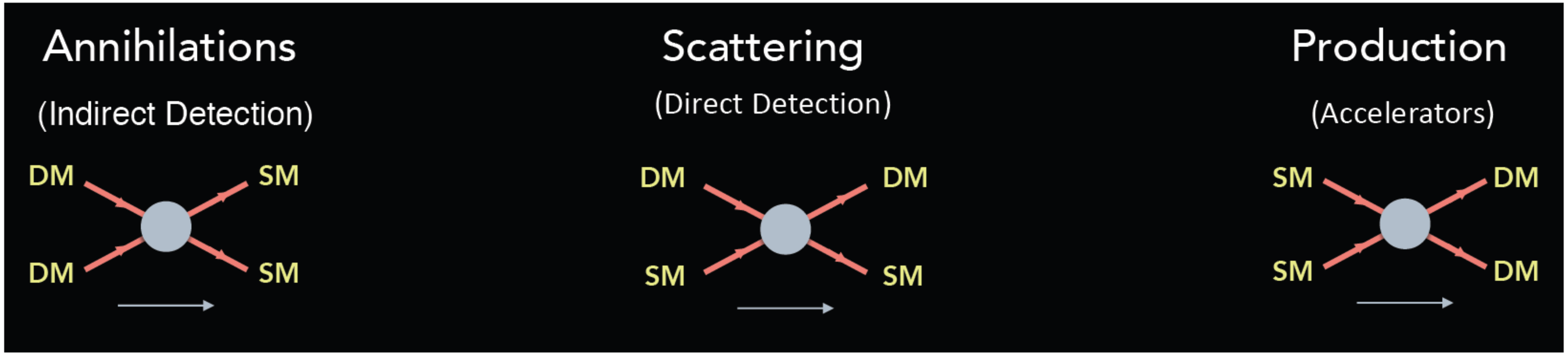


Jeans instability turned tiny density fluctuations into all visible structures



(from A.Boyarsky)

Over next few decades, important advancements in both astrophysical and terrestrial probes will test WIMPs and Dark Sectors



M. Lisanti's Talk

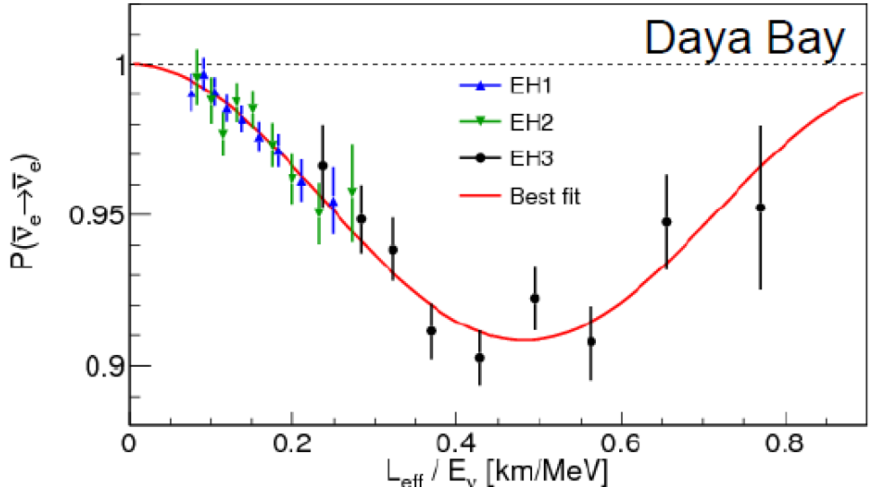
(Granada-2019 meeting)

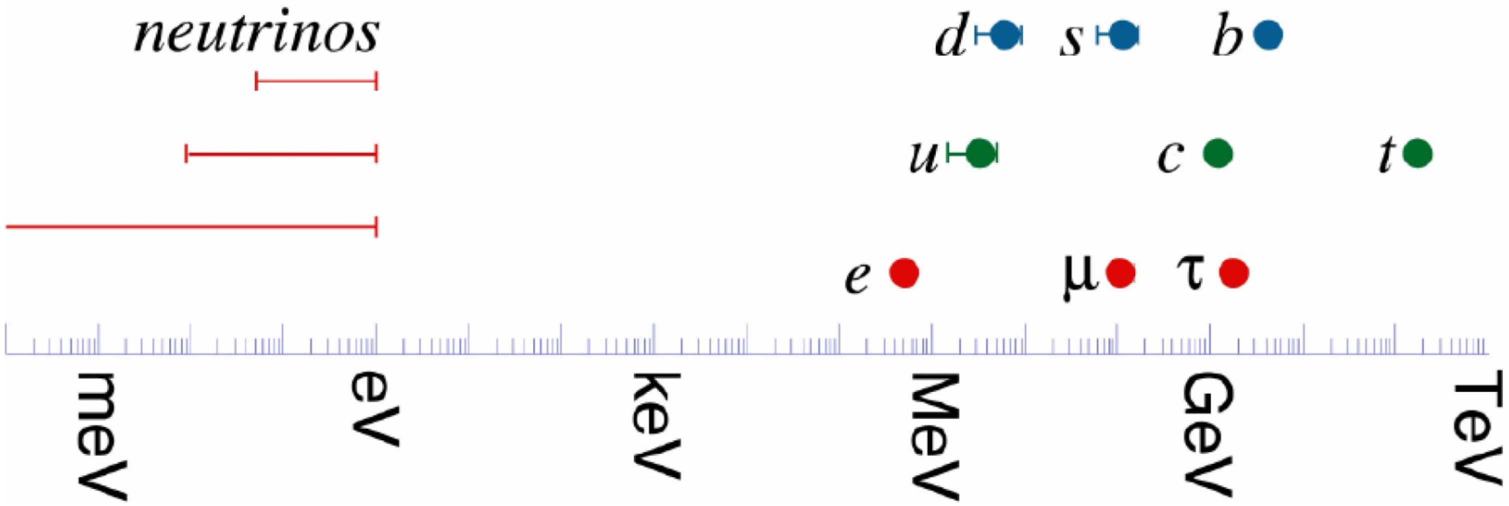
Neutrinos are massless in the SM, but massive in Nature

$$P_{\nu_\alpha\to\nu_\beta}(t)=|\langle\nu_\beta|\nu(t)\rangle|^2=\ \delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Analogously to quarks, mass eigenstates of neutrinos are superpositions of flavour eigenstates – and vice versa. However, contrary to the quark case, neutrino oscillations is a long distance phenomenon for mass differencies in sub-**eV** range:

$$\frac{\Delta m^2_{ij}L}{4E}\approx 1.267\frac{\Delta m^2_{ij}[\mathrm{eV}^2]\times L[\mathrm{km}]}{E[\mathrm{GeV}]}\qquad \Delta m^2_{ij}=m^2_i-m^2_j$$





The pattern of quark mixing, encoded in Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

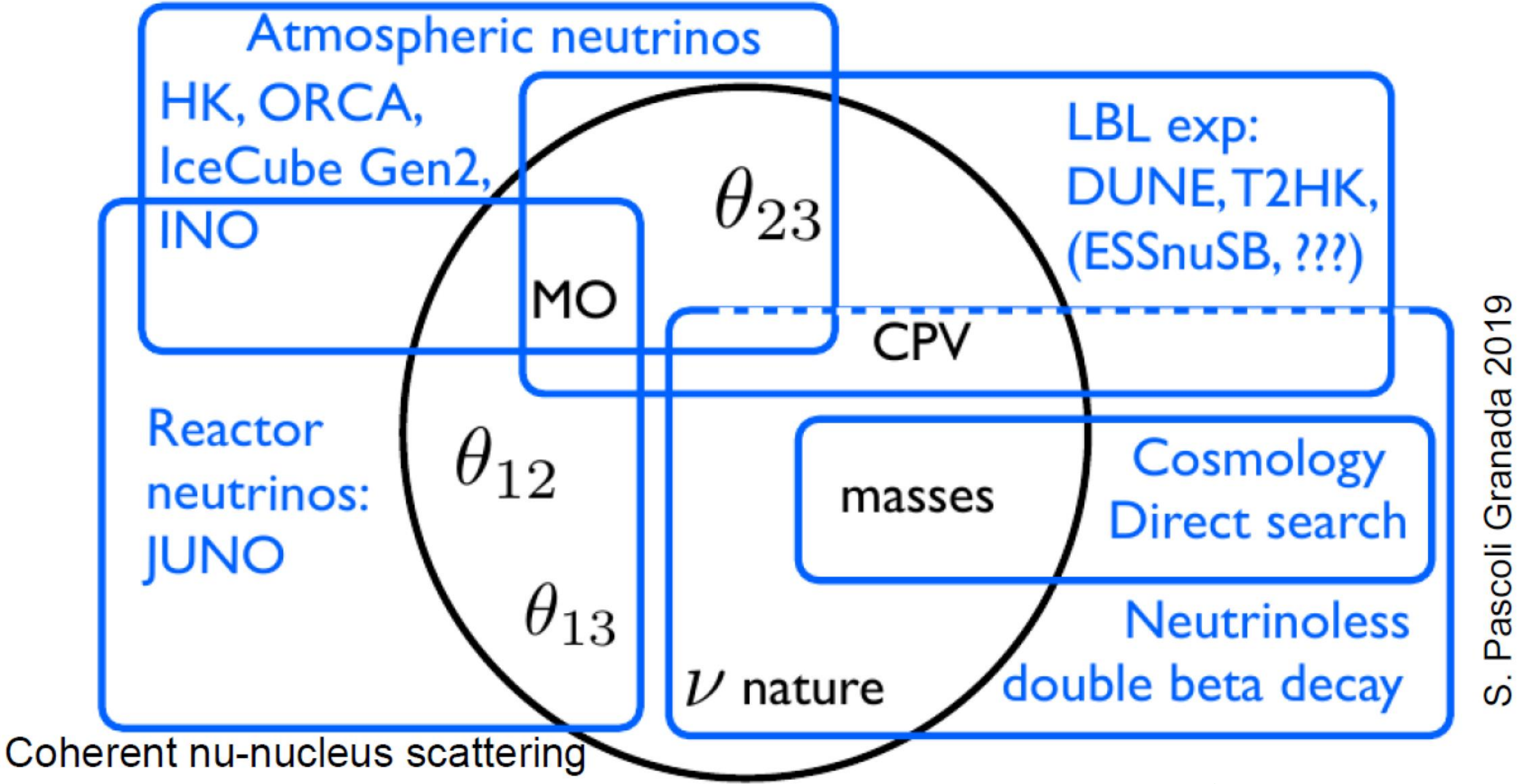
seems to be drastically different from the pattern of neutrino mixing, encoded in Pontekorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

We do not know why

There is the vibrant experimental program in neutrino physics



S. Pascoli Granada 2019

(Granada-2019 meeting)

What to do when interaction is very weak…

$^{184}\mathrm{Os}$ half-life is 5.6×10^{13} years.

Age of the Universe is 14×10^{9} years

?

N_A = 6,022 140 857(74)·10^{23} моль$^{-1}$.

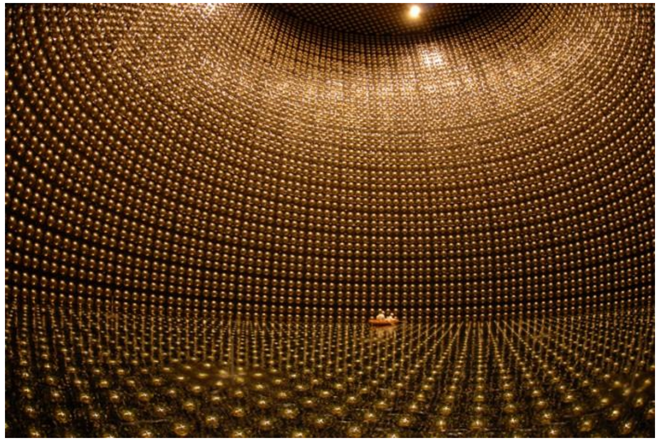
!

It is easy to have **10$^{(15\text{-}20)}$** absolutely identical atoms

$$\delta N \approx \frac{N_0 \log 2}{T_{1/2}} \delta t$$

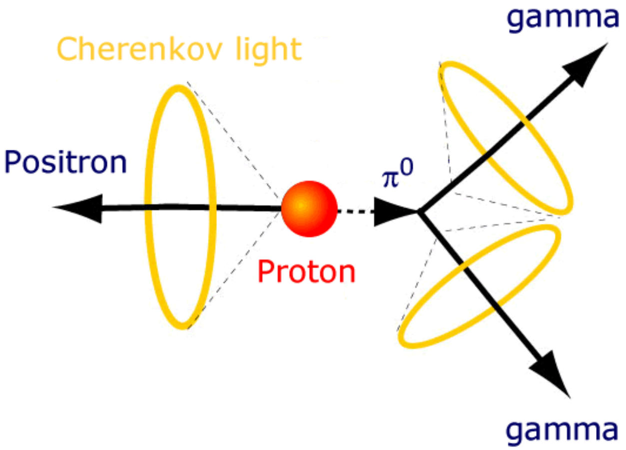
Example: proton decay search

SuperKamiokande – the underground neutrino experiment with 50 ktons of water and 13 000 photosensors



50 000 tons ~ 7×10^{33} protons.

$$\tau/\mathrm{B}_{p\to\nu K^+} > 5.9 \times 10^{33}\text{years}$$



European Strategy Update

Dark Sectors

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal

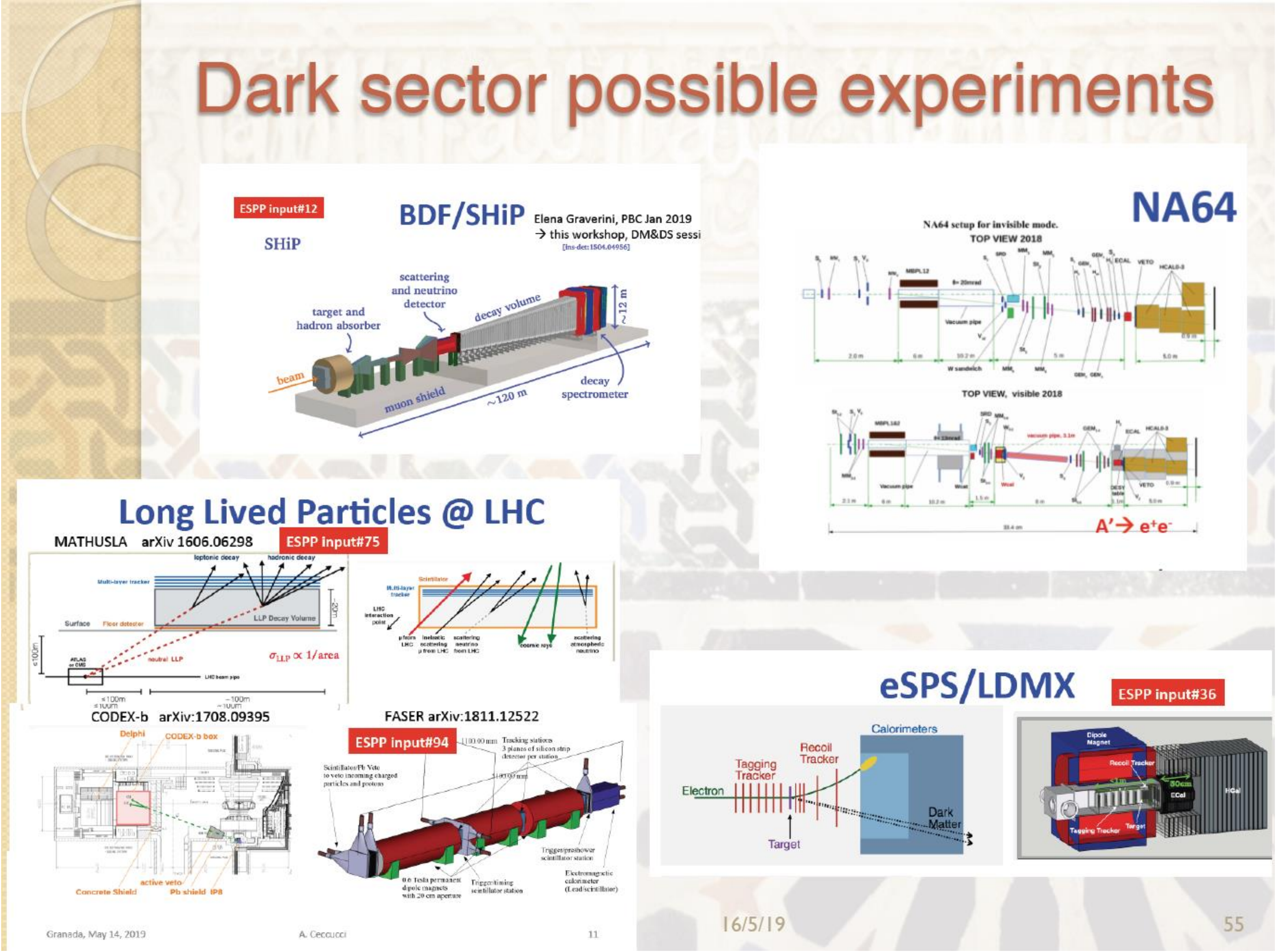

Standard Model
Portal
Dark Sector

Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP's)

(Granada-2019 meeting)



Dark sector possible experiments

ESPP input#12 **BDF/SHiP** Elena Graverini, PBC Jan 2019

→ this workshop, DM&DS sessi

[ins-det:1504.04956]

SHiP

NA64

NA64 setup for invisible mode.

TOP VIEW 2018

TOP VIEW, visible 2018

A'→ e⁺e⁻

Long Lived Particles @ LHC

MATHUSLA arXiv 1606.06298 **ESPP input#75**

CODEX-b arXiv:1708.09395

FASER arXiv:1811.12522

ESPP input#94

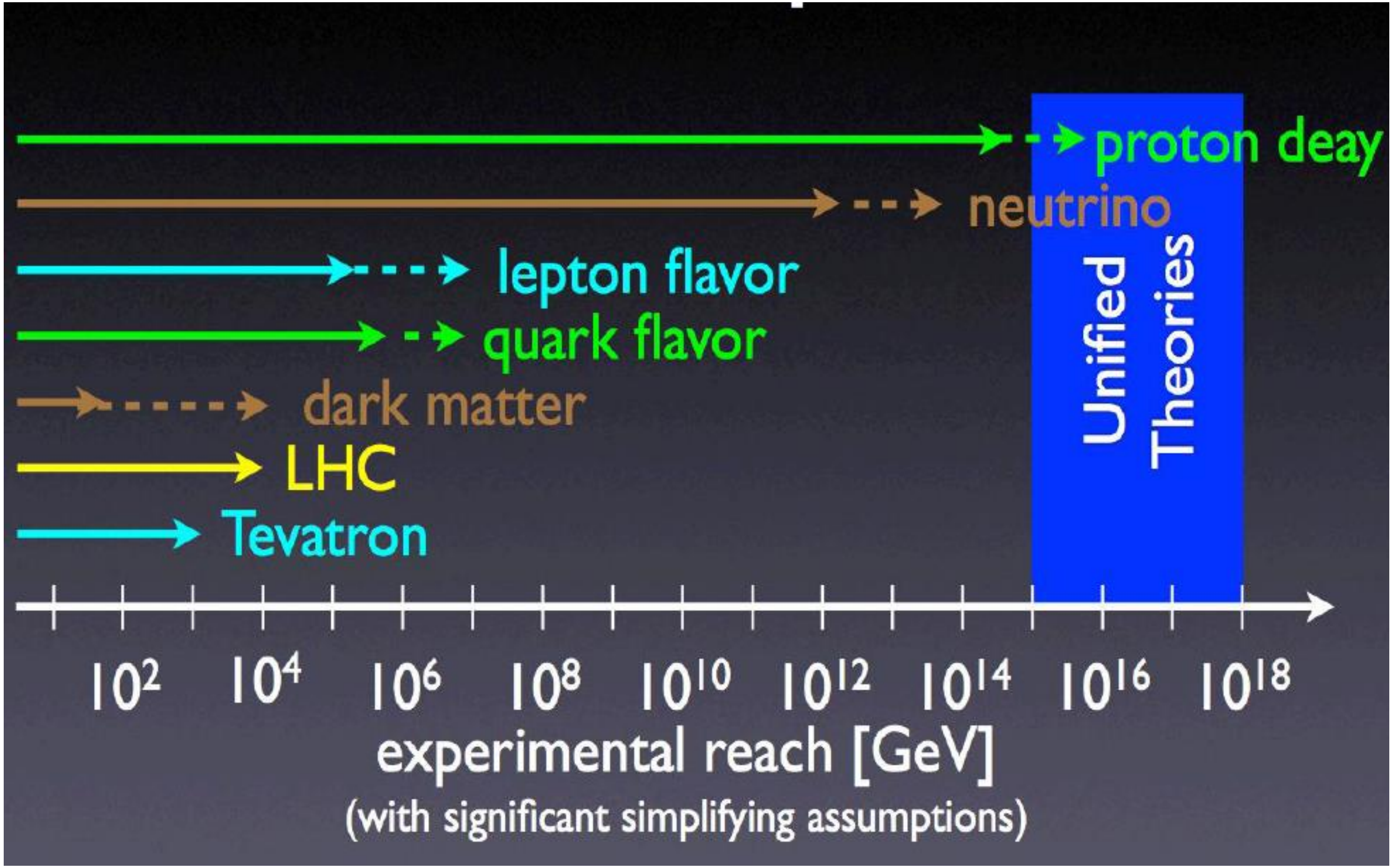
Granada, May 14, 2019 A. Ceccucci 11

eSPS/LDMX **ESPP input#36**

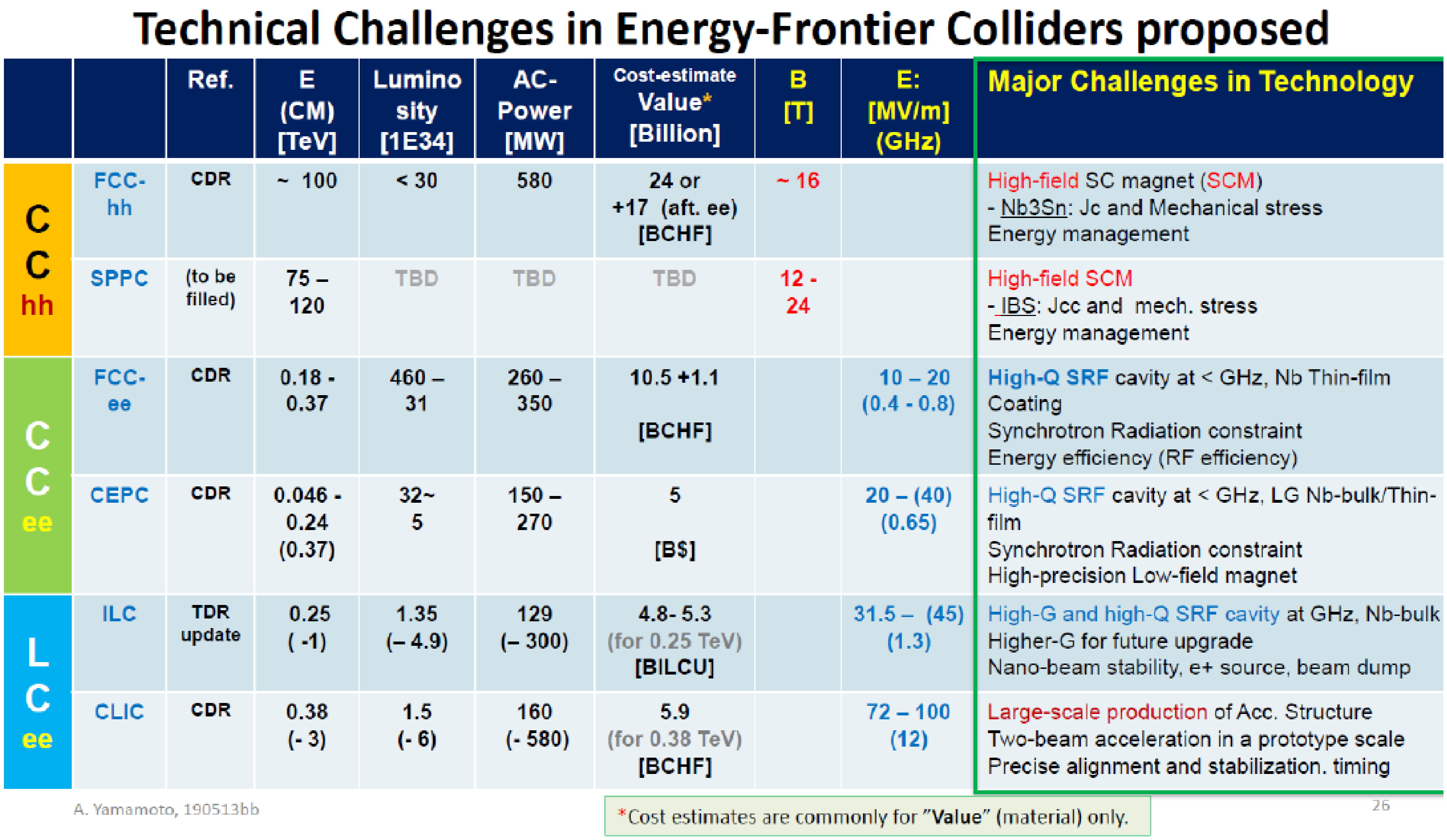
16/5/19 55

(Granada-2019 meeting)

Intensity frontier physics reach



(picture of Z.Ligeti)



Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190513bb

*Cost estimates are commonly for "**Value**" (material) only.

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Physical requirements directly transfer to technological ones

(Granada-2019 meeting)

Instead of conclusion

We need a clue where New Physics is

The word «clue» derives from «clew», an Old English word for a ball of string. It came to mean ‘a hint that aids a solution’ through allusion to the Greek legend of Theseus.

The same story is with the Russian word «клубок», which means a ball of thread.

Notice that Ariadne’s string could not help Theseus to find the Minotaur in the Labyrinth, but was extremely helpful to follow the right way out.

«The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being. But the big questions of our field remain wide open (hierarchy problem, flavour, neutrinos, DM, BAU, etc.).This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias(es).»

M. Mangano

Homework problems

- Problem 1 – slide 8
- Problem 2 – slide 11
- Problem 3 – slide 17
- Problem 4 – slide 26
- Problem 5 (slide 38): how many decays will be detected for one year in one gram of osmium?
- Problem 6 (slide 42): estimate the proton energy in Future Circular Collider (FCC-hh) for parameters from the table.
- Problem 7: Imagine you are responsible for strategic allocation of financial resources in physics of fundamental properties of matter for the next 10 years worldwide (about \$10B-\$12B) . Formulate (in written form) how you would proceed.