IPP at 50: Overview of Developments in Particle Physics

Maxim Pospelov

U of Minnesota and FTPI

(formerly at U Victoria and Perimeter)

UNIVERSITY OF MINNESOTA
Driven to Discover℠
umn.edu

Plan

1. State of Particle Physics 50 years ago.

2. Progress over decades of efforts

3. Canadian contribution to particle physics discoveries

4. Conclusions: looking forward to the next 25 years.

Particle physics 50 years ago
(at the threshold of big discoveries)

- Electromagnetism was fully understood, both at classical and quantum level; gravity was understood at the classical level (GR).

- Weak interactions in *charged currents* were identified correctly.

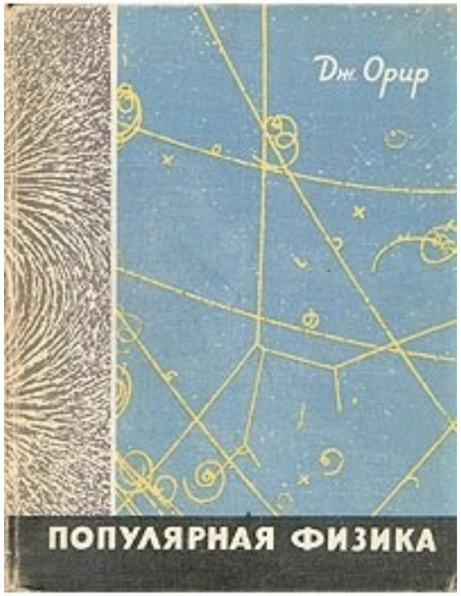
- Strong interactions, after a burst of new resonances discovered in the 60s, began to exhibit some unanticipated behavior, *scaling*, once the energy of scattered probes was raised much above the hadronic scale.

- Kaon physics revealed a number wonderful puzzles, including mysterious phenomenon of CP violation.

- Theorists began to increasingly focus on Yang-Mills theories, and a promising [if incomplete] model of weak interactions emerged.

50 years ago I was….

soon to be reading



Jay Orear, Popular Physics Russian Translation. Mid-1960s.

Conclusion: *General Relativity is beautiful*. $E=mc^2$ was ”digestible”. But particle physics is a mess. There is no organizing principle. *Why are all these particles O(50+)* ?

Late 1960s Lagrangian

$$\mathcal{L}_{\text{1960s}} = -\frac{1}{4}(F_{\text{EM}})^2 + \sum_{\psi} \bar{\psi}(\gamma_\mu D_\mu^{\text{EM}} - m - \mu(\sigma F^{\text{EM}}))\psi$$

$$-\frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma_\alpha(1-\gamma_5)\nu_e\bar{\nu}_\mu\gamma_\alpha(1-\gamma_5)\mu\right] - \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma_\alpha(1-\gamma_5)\nu_e\bar{p}\underline{\gamma_\alpha(g_V - g_A\gamma_5)}n\right] \times \cos\theta_C$$

$$+(\text{similar terms for strange particles}) \times \sin\theta_C$$

- Pretty complicated, with every new phenomenon requiring ~ extra terms added by hand.

- What to do with resonances? (Notwithstanding beautiful flavor SU(3) symmetries uncovered in the 1960s.) *Quarks were not real.*

- Promising theoretical constructions were built using spontaneous symmetry breaking mechanism by Brout, Englert, Higgs et al, and applied to Glashow's SU(2)*U(1) by Weinberg and Salam.

Breakdown of progress by decade

- 1970s. The breakthrough decade: QCD (and, yes, quarks are real), neutral currents, three generations and mixing.
- 1980s. The decade of W, Z. The solar neutrino problem takes shape.
- 1990s. Electroweak precision and the top quark discovery, and breakthroughs in observational cosmology.
- 2000s. The most flavored decade: neutrino oscillations firmly established + success of flavor factories. ΛCDM.
- 2010s. The decade of the LHC and the Higgs boson – complete triumph of the SM. Gravitational waves.

Iconic results from the past, I

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

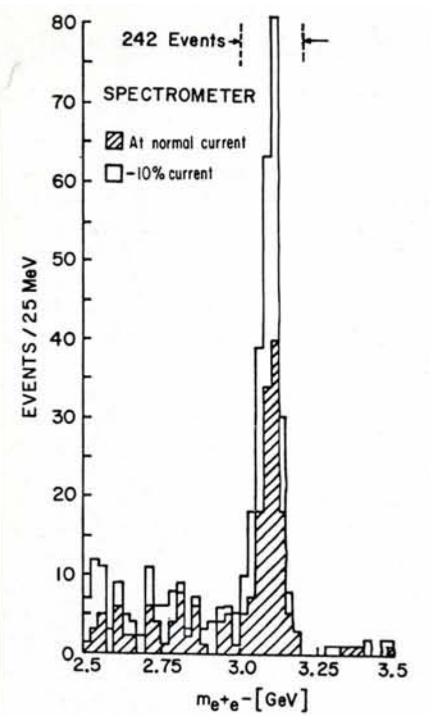
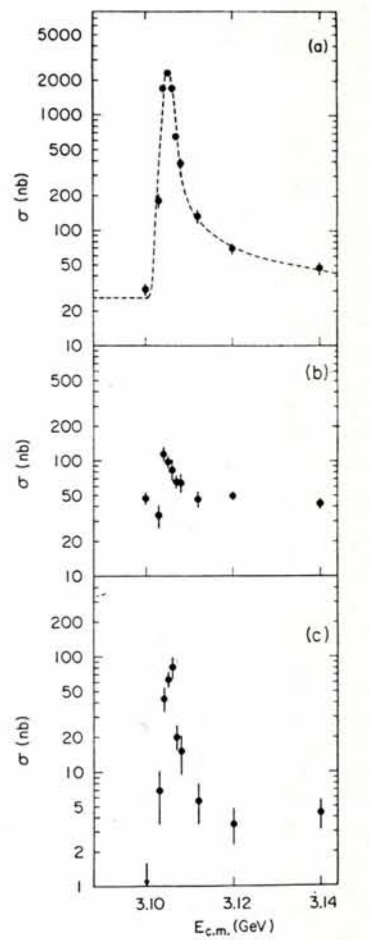


Fig. 1 The J-ψ signal detected by Ting and his group at BNL. The J-ψ appears as a quite striking peak in the distribution of the total mass of the electron-positron pairs.

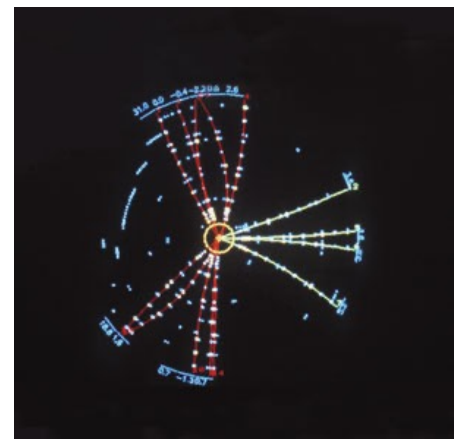


Advantages of the Color Octet Gluon Picture*

HARALD FRITZSCH†, MURRAY GELL-MANN and HEINRICH LEUTWYLER††
California Institute of Technology, Pasadena, California 91109

ABSTRACT

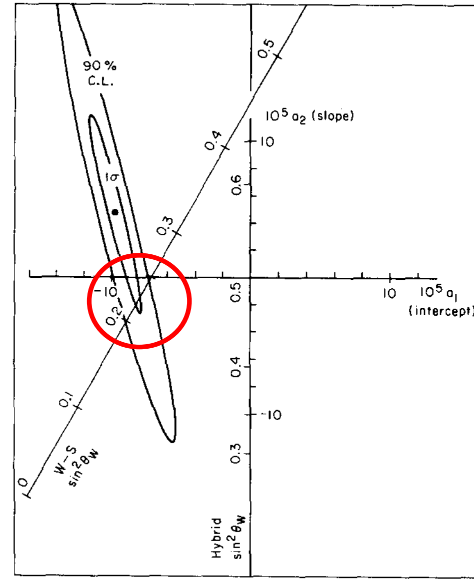
It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang-Mills gauge model based on colored quarks and color octet gluons.



Quarks and gluons are real → QCD is quasi-free at high-energy. It opens enormous possibilities.

Iconic results from the past, II

Gargamelle's neutrino Neutral Current event. $Sin^2\theta_W$ is measured



C. Prescott et al, Parity violation in EM*NC interference scattering. $Sin^2\theta_W$ is confirmed

Measurement of optical activity of bismuth vapor

L. M. Barkov and M. S. Zolotarev

Nuclear Physics Institute, Siberian Division, USSR Academy of Sciences

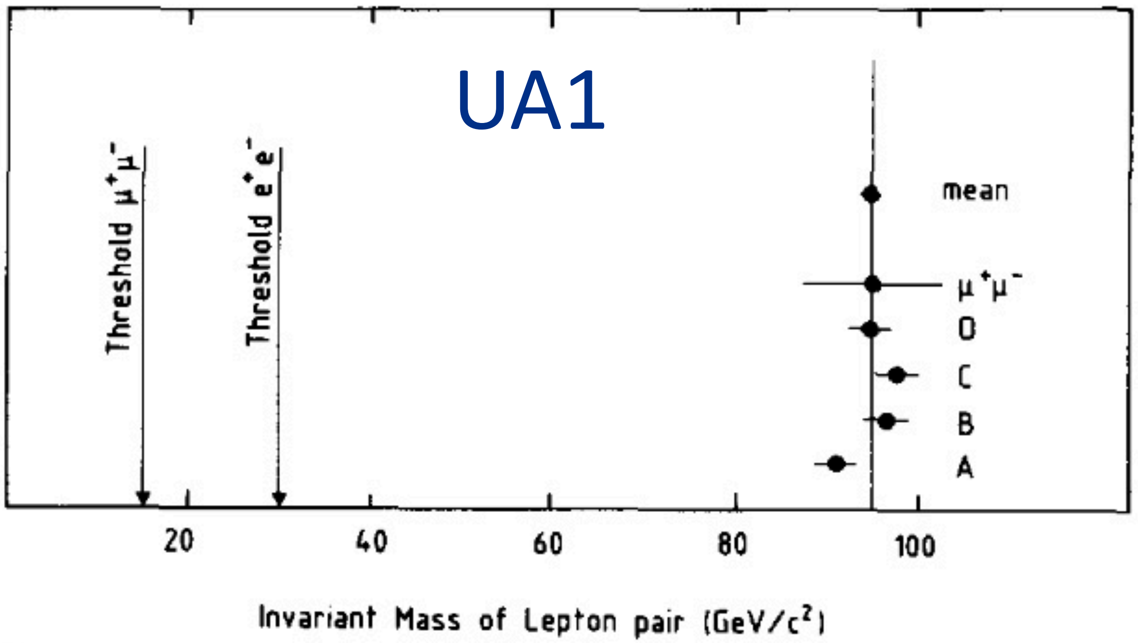
(Submitted 5 September 1978)

Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 8, 544–548 (20 October 1978)

The rotation angle $\overline{\psi_{exp}}$ was $(-3.1 \pm 0.5) \times 10^{-8}$ rad averaged over the five working lines and $(1.0 \pm 0.5) \times 10^{-8}$ rad for the seven control lines. The ratio of the measured polarization-plane rotation angles to those calculated, assuming validity of the Weinberg-Salam theory at a Weinberg angle corresponding to $\sin^2\theta_w = 0.25$ was $\overline{\psi_{exp}/\psi_{B-C}} = 1.1 \pm 0.3$ for the working lines. The averaged expected rotation angles for the control lines was 0.2×10^{-8} rad.

A model of leptons / Weinberg-Salam model → the Standard Model

Iconic results from the past, III



M_Z = 95.2 +/- 2.5 GeV

UA1/UA2 endeavor pushed into a new technological territory. W and Z are discovered and studied, pointing to the next chapter (LEP).

Canadian (IPP+$_{exp}$+$_{th}$) contributions

- UA1/UA2
- SNO
- OPAL (also SLD)
- ARGUS
- HERMES and ZEUS
- CDF
- BaBar
- Qweak, Moeller
- ATLAS
- T2K
- Super/Hyper Kamiokande
- SNO+
- Belle II
- DM detection program

Canadian (IPP$+_{exp}+_{th}$) contributions

UA1/UA2	discovery of W,Z	NP
SNO	resolution of solar ν problem	NP
OPAL (also SLD)	EW precison measurements	
ARGUS	first B-factory	NP
HERMES and ZEUS	DIS, proton structure, PDFs	
CDF	EW physics, top, B-physics	
BaBar	precision flavor, CP-violation	NP
Qweak, Moeller	precision parity	
ATLAS	Higgs+everything	NP
T2K	precision ν oscillations	
Super/Hyper Kamiokande	precision ν oscillations	NP
SNO+	solar ν, 0ν2β	
Belle II, NA62	new era in flavor, DS	
DM detection program	DM and dark sectors	

Canadian (IPP+$_{exp}$+$_{th}$) contributions

▪ UA1/UA2	discovery of W,Z	NP
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▪ SNO+	solar ν, 0n2b	
▪ Belle II, NA62	new era in flavor, DS	
▪ DM detection program	DM and DS	

Canadian (IPP+$_{exp}$+$_{th}$) contributions

Theory contributions

- Quark models (U Toronto, Guelph, Carleton).
- Precision QED, Flavor, e/ν scattering, EDM calculations (UoA, UdM, Windsor, TRIUMF, U Manitoba, St. Mary's, Victoria…)
- Dark sectors (U Toronto, U Victoria, McGill, Perimeter, TRIUMF)
- CMB, inflation, cosmology in general (U Toronto/CITA, McGill, Perimeter, McMaster)
- GR and GW (UBC, Alberta, Guelph, U Waterloo)
- String and field theory (Perimeter, UBC, McGill, U Toronto, Victoria)

SM Lagrangian, mid-1990s

$$\mathcal{L}_{\text{mid}-1990\text{s}} = \text{SM } \mathcal{L} \text{ contains all terms consistent with the Scripture}^*$$

*The Scripture: Standard Model Lagrangian includes all terms of canonical dimension 4 and less, consistent with three generations of quarks and leptons and the SU(3)*SU(2)*U(1) gauge structure at classical and quantum levels.

- Higgs is still missing. Alternatives (e.g. strong coupling at a TeV) are not fully dead.
- CP violation may be CKM, but may be superweak (?)
- Neutrinos are misbehaving (deficit of solar and atmospheric ν)
- GGdual QCD terms is missing (no EDMs). Strong CP problem.

Solar neutrinos, neutrino oscillations

- After R. Davis' experiment – that first detected solar (i.e. non-reactor) neutrinos, but not enough of them as per J. Bahcall's calculations – W. Fowler remarked: "*We think, if Ray improves the sensitivity of his equipment, he'll find the neutrinos all right*".

- Some particle theorists were very skeptical of the whole endeavor:

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

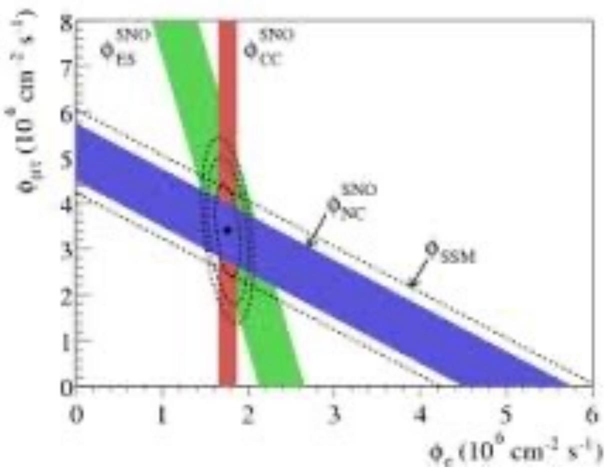
Received 17 April 1990

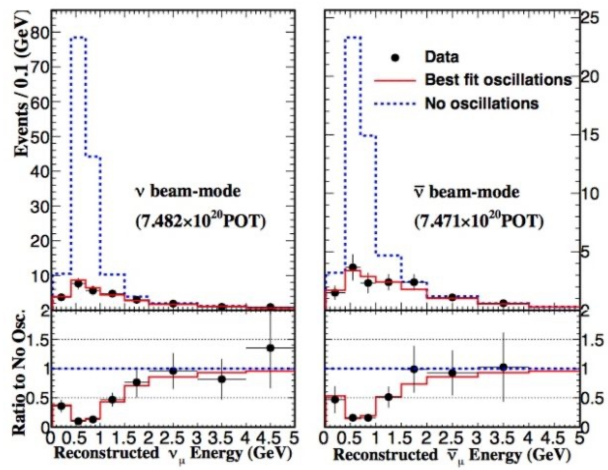
1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent

- The SNO experiment – a long time effort – finally resolved the paradox in favor of the flavor oscillation hypothesis.

Implications of ν oscillation discovery





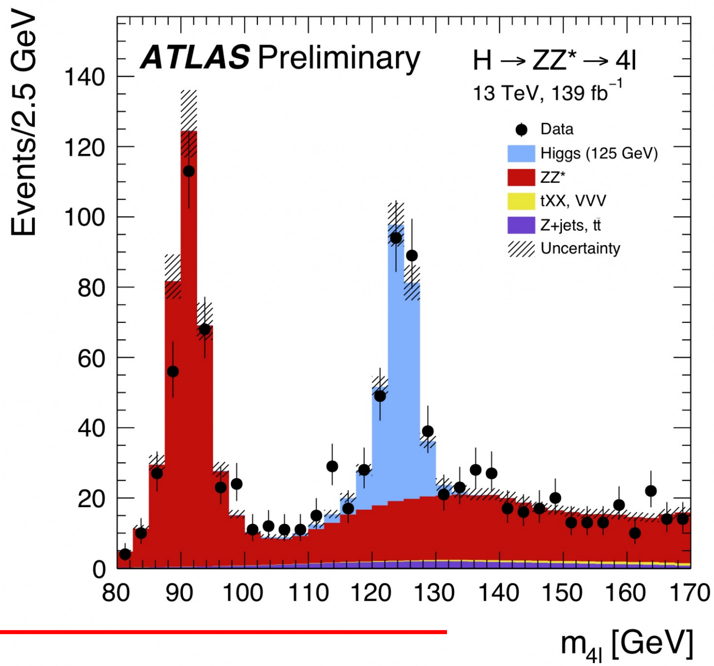
- We need to do something to the theory: e.g. add new singlet neutrino fields, or at least a *higher dimensional* operator

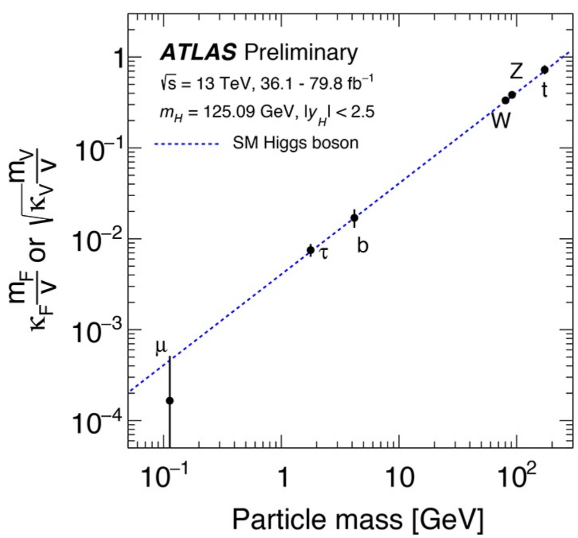
$$m_{\nu,\mathrm{D}}\bar{\nu}\nu \quad \longrightarrow y_\nu \bar{N}\nu H + (h.c.)$$

$$m_{\nu,\mathrm{M}}\bar{\nu}\nu \quad \longrightarrow (y_\nu)^2(\nu H)^c \times \frac{1}{m_N} \times (\nu H) + (h.c.)$$

- Both are valid options – only experiment (e.g. ν02β decays, SNO+) can help distinguishing between these scenarios
- New mixing matrix implies new CP-odd phases, which could be related to the emergence of matter-antimatter asymmetry via leptogenesis. Stay tuned for the Hyper-K based program.

EW precision → top and Higgs





- There was a strong, O(15 GeV), for the top and mild, $m_H = 90^{+21}_{-19}$ GeV for the Higgs, prior from precision measurements of α, G_F, m_Z/m_W and other EW precision observables.

- Incidentally, it is a "maximally interesting" Higgs mass, offering a possibility of precision measurements for many decay modes. More from the LHC and ATLAS!

- Elementary Higgs exchange mediates a qualitatively new force of nature, the fundamental Yukawa force, with the coupling ~ mass.

Implications of Higgs discovery [and nothing else]

- *No hints for any kind of new physics.* Strong constraints on SUSY, extra dimensions, technicolor resonances, new Z' etc.

- There is no "clear practical guidance" that can be derived from the Higgs naturalness problem. If it is a "common-scale" SUSY, the particular value of the Higgs mass implies multi-10 TeV scale for superpartner masses.

- Lots of work remain to be done (e.g. demonstrate that the Higgs-self interaction strength is consistent with the SM).

- Develop a strategy of testing SM as an effective theory (trying to see the deviations before asking for a new collider) – *my personal opinion*

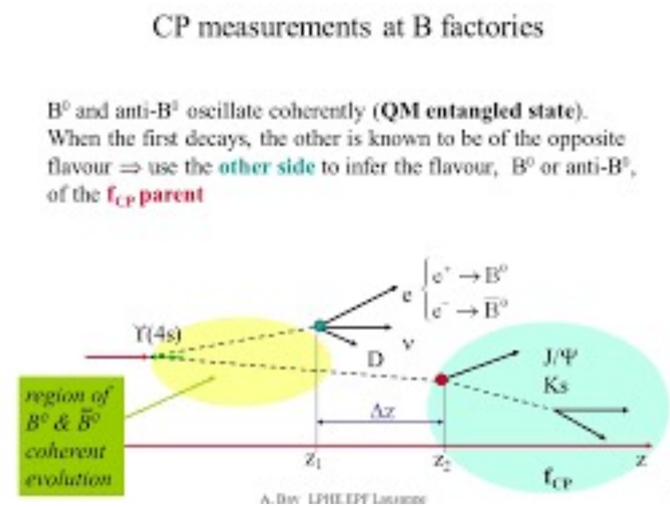
CP violation and flavor and implications

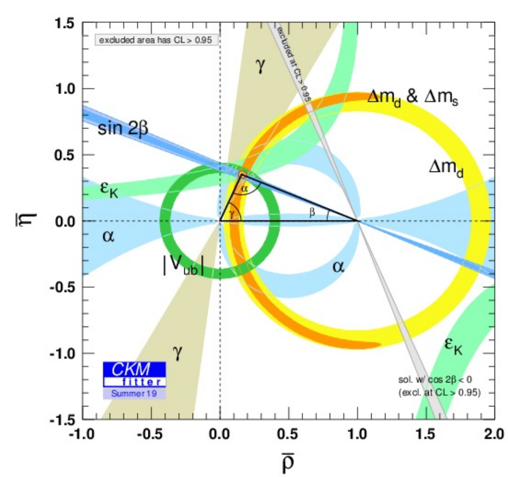
- For a long time the field was dominated by K_L → ππ measurement that could be from δ_{CKM}.

$$\frac{e^{i\phi}}{\Lambda_{SW}^2}(\bar{d}s)(\bar{d}s), \text{ i.e. "superweak" type}$$

$$V_{CKM} \neq V_{CKM}^*, \text{ Kobayashi – Maskawa phase}$$

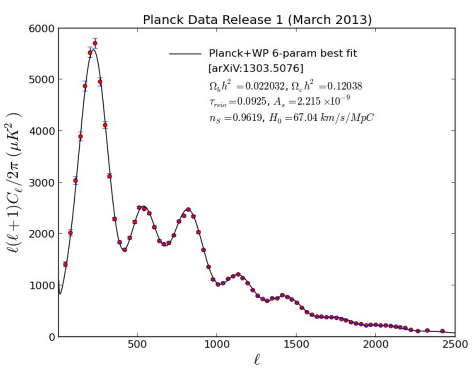
- The break came in late 1990s when ε’/ε was finally measured, and almost immediately by BaBar and Belle providing a win for CKM physics (and using quantum technology in the process)
- Today’s precision (aided by the LHCb) exceeds initial expectations, consistent with SM. (But! Watch R_{K,K^*,D,D^*} anomalies) To be checked even more accurately by Belle II, NA62 etc.
- EW baryogenesis implies flavor diagonal CP violation → EDM@Triumf



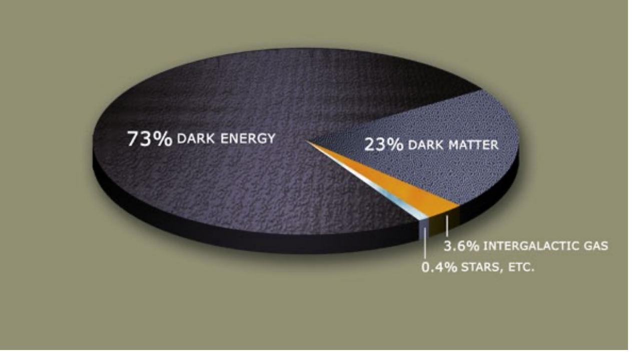


Lesson from precision cosmology:

- Universe was relatively *simple* at T ~ 0.3 eV.
- The dark matter was already "*in place*" at the time of the matter-radiation equality, when the potential wells created by DM started to grow. We see statistical evidence of H and He falling (and rebounding) from the DM gravitational wells. The amount of He and D is consistent with primordial nucleosynthesis
- DM is not "made of ordinary atoms" – and there is 6 times more of it than of ordinary H and He. $\Omega_{\text{dark matter}} / \Omega_{\text{baryons}} = 5.4$
- What is it? These are *not* known neutrinos: they would have to weigh ~ 50 eV (excluded), and would have a hard time making smaller scale structure (too hot to cluster on small scales).



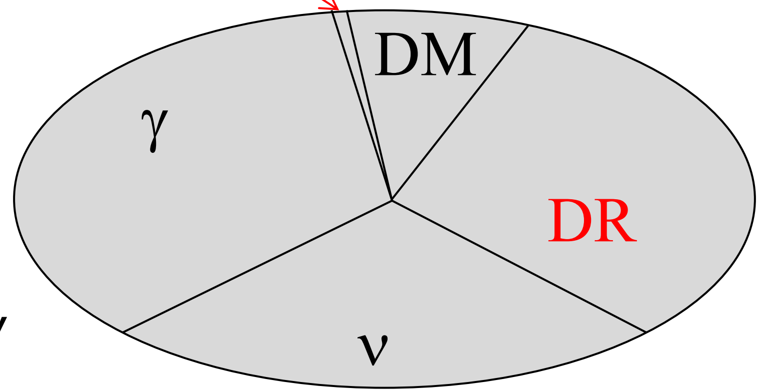
Simplicity of the early Universe, makes many of us suspect that the DM might be in the form of unknown (= e.g. beyond-SM) particles.



Cosmology determines mass density (and sometimes spectrum/temperature) of different species

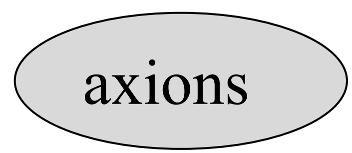
Atoms

In Energy chart they are 4%. In number density chart ~ 5 $\times 10^{-10}$ relative to γ



We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation, Dark Forces – Who knows!).

Number density chart for axionic universe:



Cosmological puzzles motivate terrestrial search experiments (Experiments at Snolab)

Motivations for Axion-like particles

- Initially suggested (QCD axion) to solve the strong CP to problem by relaxing the effective QCD vacuum angle theta to zero.

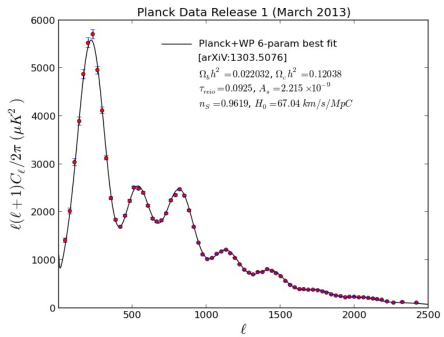
$$\theta_{QCD} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} \longrightarrow \left(\theta_{QCD} + \frac{a}{f_a}\right) G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

- Can easily constitute the entirety (or a fraction) of cold dark matter.

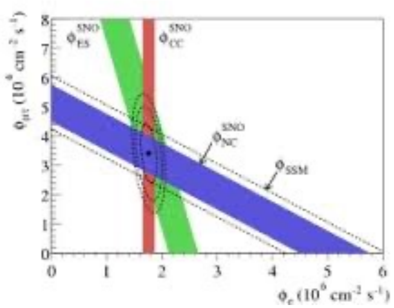
- More massive versions of ALPs could still provide [limited] solution to the strong CP, while being stronger coupled and amenable to beam dump and rare decay searches (NA62, Belle II).

If your SM works so well, why do you want it to be broken?

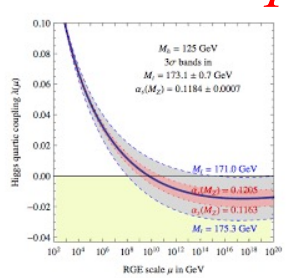
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM, and can lead to lepton number violation.



3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



4. *"Anomalous results":* muon g-2, B-physics anomalies, SBN neutrino anomalies, Hubble constant tension etc.

SM as an Effective Field Theory

Typical BSM model-independent approach is to include all possible BSM operators + light new states explicitly.

$\mathcal{L}_{2020s}$ = - m_H^2 $(H^+_{SM} H_{SM})$ + all dim 4 terms $(A_{SM}, \psi_{SM}, H_{SM})$ +

Neutrino mass operators (e.g. effective Dim=5)

+(W.coeff. /Λ^2) × Dim 6 etc $(A_{SM}, \psi_{SM}, H_{SM})$ + …

all lowest dimension portals $(A_{SM}, \psi_{SM}, H, A_{DS}, \psi_{DS}, H_{DS})$ × portal couplings

+ dark sector interactions $(A_{DS}, \psi_{DS}, H_{DS})$

SM -- Standard Model

DS – Dark Sector

How to look for New Physics ?

1. High energy colliders.

2. Precision measurements when a symmetry is broken

3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA64) can be searched.

4. DM searches

All three strategies are being actively pursued by particle physics community.

How to look for New Physics ?

1. High energy colliders.

$$\frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q) \;\rightarrow\; \sigma \propto \frac{E^2}{\Lambda^4} \;\rightarrow\; \Lambda > 10\,\mathrm{TeV}$$

2. Precision measurements when a symmetry is broken

$$\frac{1}{\Lambda_{\mathrm{CP}}^2}(\bar{e}i\gamma_5 e)(\bar{q}q) \;\rightarrow\; \mathrm{EDM},\, \frac{1}{\Lambda_{\mathrm{CP}}^2} < 10^{-10}G_F \;\rightarrow\; \Lambda_{\mathrm{CP}} > 10^7\,\mathrm{GeV}$$

3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA64) can be searched.

$$pp \;\rightarrow\; \pi, K, B \;\rightarrow\; HNL + X \;\rightarrow\; HNL \text{ decay to SM}$$

4. DM searches: *Atom + DM* → *visible energy*

All four strategies are being actively pursued by particle physics community, with Canadian physicists often playing prominent role.

Conclusions: next 25 years

- They promise to be interesting: anchored by the LHC research program and aided by a variety of important experiments at lower energy.

- We are likely to see more departure from the SM_{1967}, in addition to neutrino masses and mixing. Where would this break come from: LHC, DM program, EDMs, rare decays, PNC at part-per-billion level, dark sector studies, next series of precision cosmology observation?

- New technological advances may come and change our field: new accelerating technologies, quantum technologies, continuing improvement in AMO precision, increased accessibility for the near-orbit experiments in space etc. *Stay tuned.*