From Flavors To The Origin Of The Universe

从粒子"味道"到宇宙起源

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味物理前沿研讨会暨味物理讲座100期特别活动

Workshop on Flavor Physics and the 100th Lecture on Flavor Physics

Sanya, Hainan, 30/1-4/2, 2026

摘要

基本粒子是构成宇宙的基本要素，不同的基本粒子，即粒子的“味道”以及它们之间的相互作用决定我们的宇宙的起源，演化以及我们赖以生存的宇宙的“味道”. 本演讲将从基本粒子和宇宙学的标准模型出发，展开一场色香味俱全物理寻根之旅，着重味物理中包含夸克，轻子，中微子,希格斯以及传递相互作用的规范粒子，特别是CP破缺，新物理寻找等面临的挑战,以及对近期突破的一些展望.

More details to come from later talks of this meeting

味物理前沿研讨会暨味物理讲座100期特别活动

Workshop on Flavor Physics and the 100th Lecture on Flavor Physics

1. Flavor physics, what it is about and where are we

2. Flavor physics and CP violation

3. Flavor physics and new physics beyond SM

4. Flavor physcis and the origin of the Universe

5. Discussions

1. Flavor Physics, what it is about and where are we?

What are flavors? The usual fundamental particle physics view

Flavor of particles: The SM of Elementary Particles

Fundamental Interactions:

Electromagnetic Interaction, mediator: Photon γ

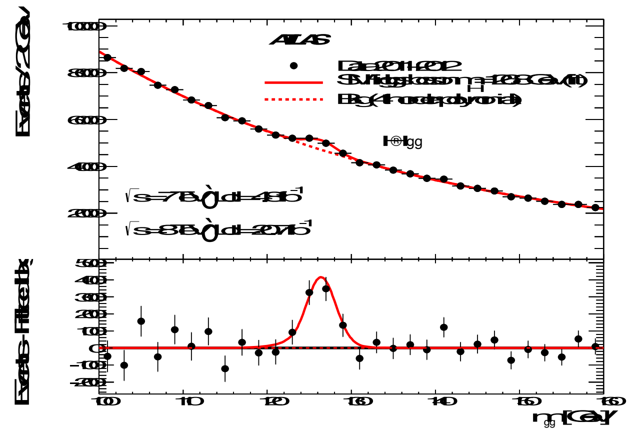
Weak Interaction, mediators: W and Z bosons

Strong interaction, mediator: gluon g

Gravitational Interaction, mediator: Graviton G(?)

Particle mass generating mechanis:

Higgs Mechanism (God particle reveals it); h



Quarks: The building block of Hadrons

u c t (electric charge +2/3 e) Quarks are elementary particles

d s b (electric charge -1/3 e) Three generations/families

Leptons: Particles have no strong interaction

ν_e ν_μ ν_τ (electric charge 0 e) Leptons are elementary particles

e μ τ (electric charge -1 e) Three generations/families

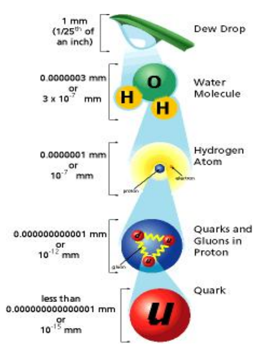
34 mobel prizes!

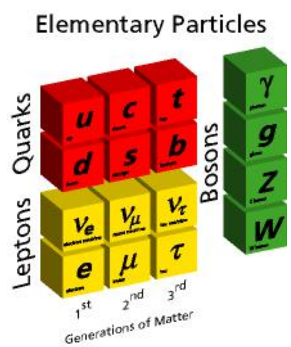
The SM of strong and electroweak interactions

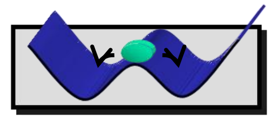
SU(3) x SU(2) x U(1) gauge theory for strong and electroweak interaction

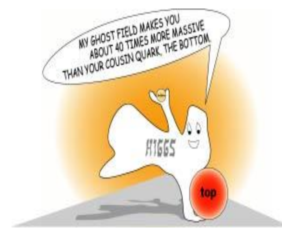
Glashow, Weinberg and Salam

Inward Bound









$G:(8,1,0),\ \ W:(1,3,0),\ \ B:(1,1,0);$

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} : (3,2,1/6),\ \ u_R(3,1,2/3),\ \ d_R)3,1,-1/3);$

$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} : (1,2,-1/2),\ \ e_R(1,1,-1);$

$H = \begin{pmatrix} (v+h+iI)/\sqrt{2} \\ h^- \end{pmatrix} : (1,2,-1/2),$

$I, h^{\pm}$ "eaten" by Z and $W^{\pm}$.

Parity violation, a coner stone of SM: 70 years of pairty violation, 1956, Lee and Yang.

Can one negeclects gravitation interaction when studying particle interactions?
The coulomb force between two protons: $Fc= e^2/r^2$,
And Gravitational force: $Fg=-Gm^2/r^2$ $|Fg|/|Fc| = 7x10^{-38}$

Gravitational force is much weaker than electromagnetism!

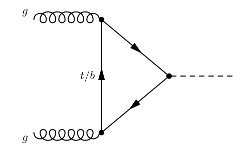
But when study cosmology, gravitational force always add up, but electromagnetism can cancel between positively and negatively charged particles! At large scale and electromagnetically neutral system, like our universe, gravitational effects dominate!

This is a model for flavor for the known basics building blocks of our Universe!

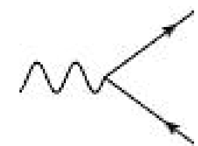
The number of genrations

In the SM, only 3 generations of quarks and leptons are allowed.

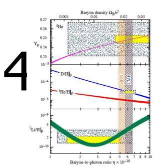
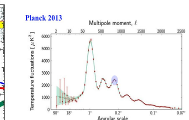
gg -> Higgs ~ (number of heavy quarks)^2, if fourth generation exist, their mass should be large, 9 times bigger production of Higgs. LHC data ruled out more than 3 generations of quarks.



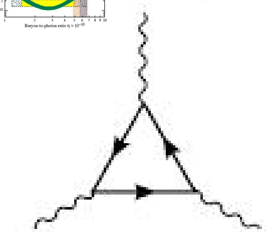
LEP already ruled out more than 3 neutrinos with mass less than $m_Z/2$.



Cosmology and astrophysics, number of light neutrinos also less than 4

SM, triangle anomaly cancellation: equal number of quarks and leptons!

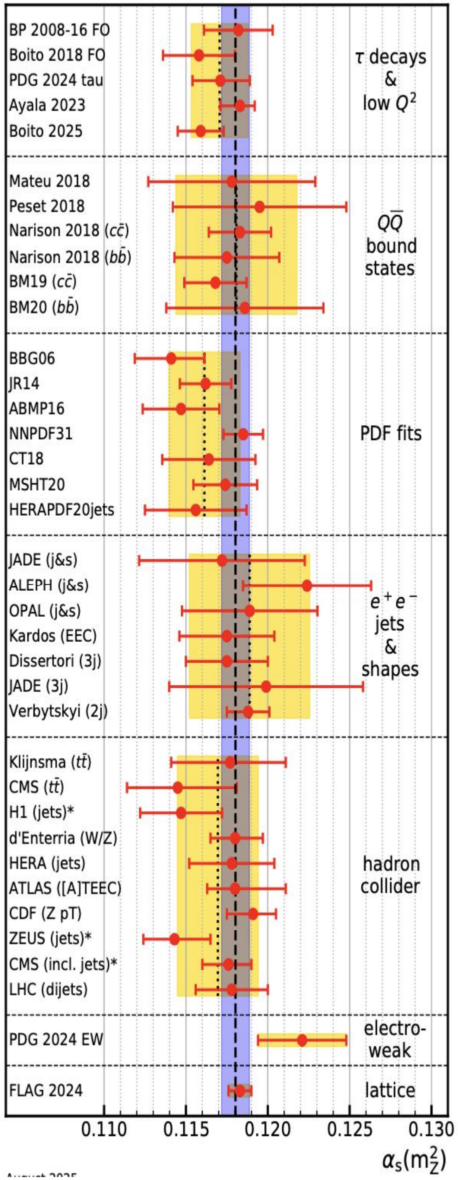


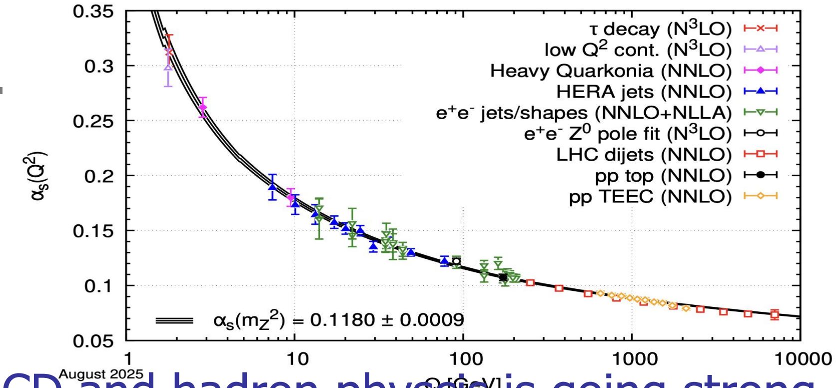
There are only three generations of sequential quarks and leptons!

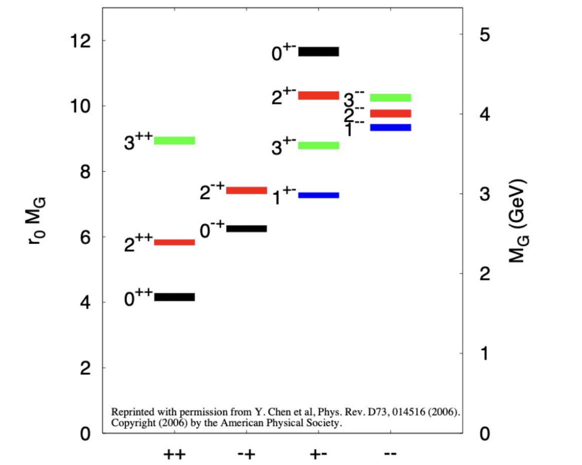
Why 3 generations? How do they mix with each other?

Beyond SM, conclusions may change, X-G He and G. Valencia, PPLB707 (2012)

QCD and hadron physcis







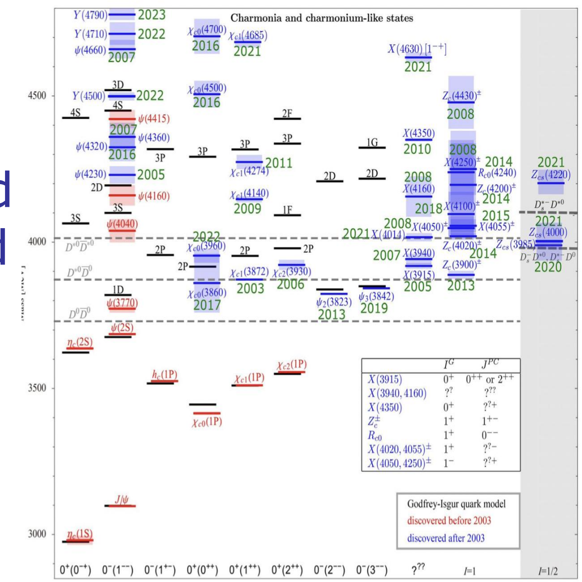
Predicted glueball spectrum from the lattice in quenched approximation

QCD and hadron physcis is going strong. α_s running established and measured to good precision!

Lattice started doing real physics, hadron spectroscopy, even parton distribution!

A lof XYZ particles discovered, tightly bound or molecular states? gluball to be discovered soon?

Yet, QCD confiment direct understanding a question STCF needed to provide more data to answer many related questions!



Weak Interactions

Parameters in the standard model with 3 generations

Gauge boson couplings and masses: $g_1=g'$, $g_{2=g}$, $g_3=g_s$, m_γ, m_W, m_Z

Fermion Masses: m_e, m_μ, m_τ, $m_{\nu e}$, $m_{\nu\mu}$, $m_{\nu\tau}$

m_u, m_d, m_c, m_s, m_t, m_b

Higgs boson mass and couplings: m_h or λ, m_i/v to ith fermion

(Weak mixing angle θ_W: $\tan\theta_W = g_2/g_1$, $e = g_2 \sin\theta_W$)

$\alpha_{em} = e^2/4\pi$, $\alpha_2=g_2^2/4\pi$, $\alpha_3=\alpha_s=g_s^2/4\pi$; $G_F = g_2^2/(\sqrt{2}\ m_W^2)$

Mixing: quark mixing (3 mixing angles + 1 Dirac-phase)

Neutrino mixing (3 mixing angles +1 Dirac-phase + 2 Majorana-phases)

1 possible strong CP violating parameter θ : $\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$

Total independent model parameters: 18 +1 without neutrino masses.

Another 9 if include neutrino masses at low energies or more.

(3 gauge couplings + 1 W or Z mass + 1 Higgs coupling or Higgs mass + (6 quark + 3 charged lepton masses)
+ 3 quark mixing angle + 1 Dirac-phase, 1 strong phase, and 3+6 neutrino masses, mixing angles and phases)

In the SM flavor physics has a lot to do with these free parameters

What do we know about the SM parameters?

Many are well measured

α_{em}=1/137.035999084(21) $\sin^2\theta_W$=0.23121(4) α_3=0.1179(9) (G_F = 1.1663788(6)x10^{-5} GeV^{-2})

m_Z=91.1876(21) GeV m_h=125.25(0.17) GeV m_W=80.357(6) GeV

Charged lepton masses:

m_e=0.51099895000(15) MeV m_μ=105.6583755(23) MeV m_τ= 1776.86(12) MeV

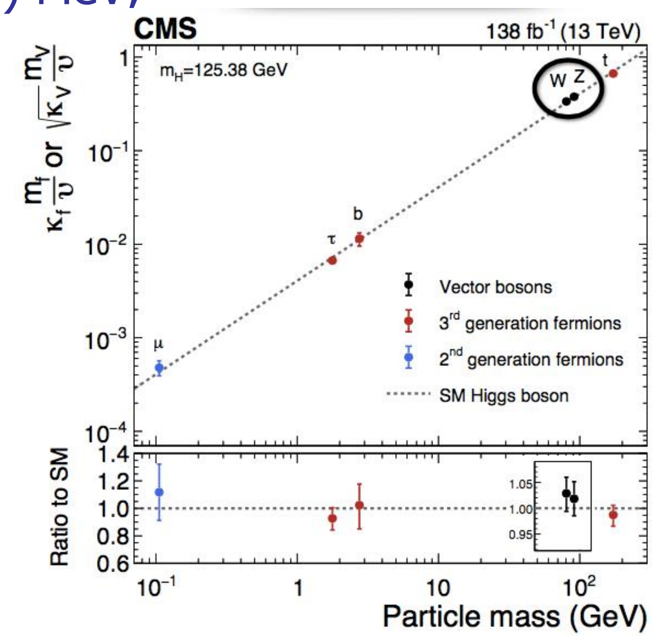
Quark masses:

light flavor: m_u =1.16(+0.49, -0.26) MeV m_d=4.67(+0.48, -0.17) MeV,

m_s=93.4(+8.6, -3.4) MeV,

Heavy flavor: m_c=1.27(0.02) GeV, m_b=4.18(+0.03,-0.02) GeV,

m_t= 172.69(0.30) GeV



Higgs sector, all data with agree SM Higgs. No nned of more Higgs!

Strong CP violating phase $\theta < 10^{-9}$

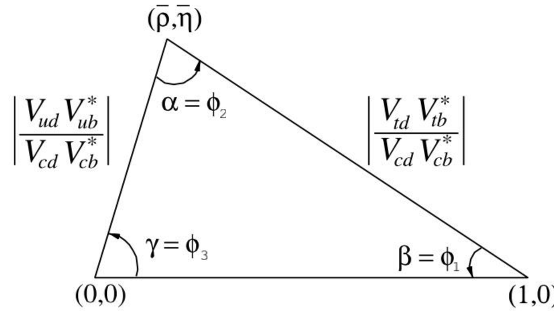
What about quark and neutrino mixing angles and CP violating phases, and neutrino masses?

Quark and Lepton mixing patterns

The mis-match of weak and mass eigen-state bases lead quark and lepton mix within generations.

Quark mixing the Cabibbo -Kobayashi-Maskawa (CKM) matrix $V_{\rm CKM}$,

lepton mixing the Pontecorvo -Maki-Nakawaga-Sakata (PMNS) matrix $U_{\rm PMNS}$



$$L = -\frac{g}{\sqrt{2}}\overline{U}_L\gamma^\mu V_{\rm CKM} D_L W_\mu^+ - \frac{g}{\sqrt{2}}\overline{E}_L\gamma^\mu U_{\rm PMNS} N_L W_\mu^- + H.C. \,,$$

$U_L = (u_L, c_L, t_L, ...)^T$, $D_L = (d_L, s_L, b_L, ...)^T$, $E_L = (e_L, \mu_L, \tau_L, ...)^T$, and $N_L = (\nu_1, \nu_2, \nu_3, ...)^T$

For n-generations, $V = V_{\rm CKM}$ or $U_{\rm PMNS}$ is an $n \times n$ unitary matrix.

A commonly used form of mixing matrix for three generations of fermions is given by $V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ are the mixing angles and δ is the CP violating phase.

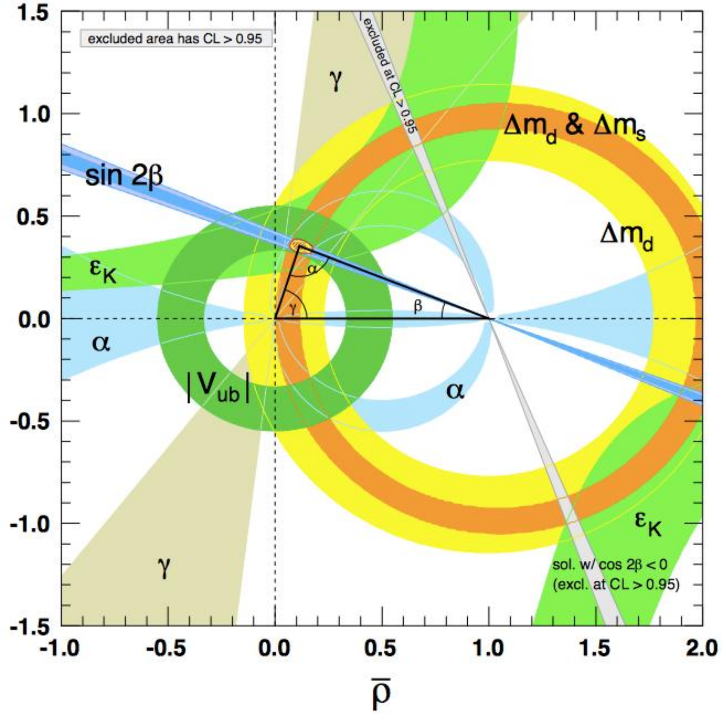
If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal

matrix with two Majorana phases $\text{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied to the matrix from right in the above.

Status of Quark and Lepton Mixing

Quark Mixing — PDG — Neutrino Mixing

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



$$\lambda = 0.22500 \pm 0.00067\,, \qquad A = 0.826^{+0.018}_{-0.015}\,,$$

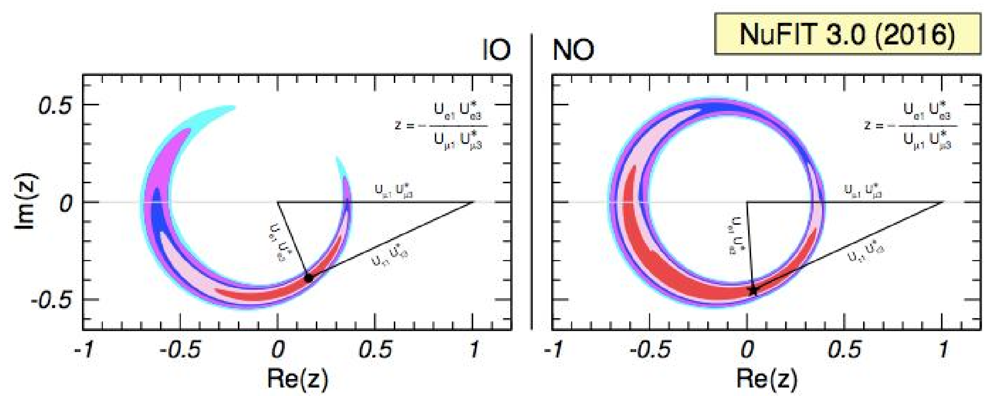
$$\bar\rho = 0.159 \pm 0.010\,, \qquad \bar\eta = 0.348 \pm 0.010\,.$$

$$\sin\theta_{12} = 0.22500 \pm 0.00067\,, \qquad \sin\theta_{13} = 0.00369 \pm 0.00011\,,$$

$$\sin\theta_{23} = 0.04182^{+0.00085}_{-0.00074}\,, \qquad \delta = 1.144 \pm 0.027\,.$$

$\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2 > 0$, if $m_1 < m_2 < m_3$ and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit	3σ
Δm_{21}^2 [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))



Why they mix the pattern shown above?

Neutrino Physics

New exciting data from Juno, last Nov. the most preciese data for θ_{12}

arXiv: 511.14593 Already 43 citations: $\sin^2\theta_{12} = 0.3092 \pm 0.0087$ and $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \mathrm{eV}^2$

$$V_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \quad V_b = \begin{pmatrix} \frac{2c}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{2s}{\sqrt{6}}, e^{i\alpha} \\ -\frac{c}{\sqrt{6}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{1}{\sqrt{3}} & \frac{c}{\sqrt{2}} - \frac{s}{\sqrt{6}}e^{i\alpha} \\ -\frac{c}{\sqrt{6}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{1}{\sqrt{3}} & -\frac{c}{\sqrt{2}} - \frac{s}{\sqrt{6}}e^{i\alpha} \end{pmatrix}, \quad V_c = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{c}{\sqrt{3}} & \frac{s}{\sqrt{3}}e^{i\alpha} \\ -\frac{1}{\sqrt{6}} & \frac{c}{\sqrt{3}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{c}{\sqrt{2}} + \frac{s}{\sqrt{3}}e^{i\alpha} \\ -\frac{1}{\sqrt{6}} & \frac{c}{\sqrt{3}} + \frac{s}{\sqrt{2}}e^{-i\alpha} & -\frac{c}{\sqrt{2}} + \frac{s}{\sqrt{3}}e^{i\alpha} \end{pmatrix}$$

Popular model in early 2000, ruled out by Dayabay Data

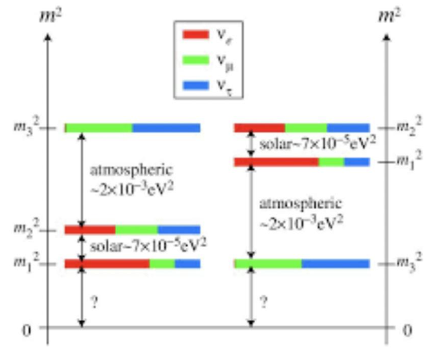
Simple and popular candidate, now 3.6 tension with data

Compatible with data!

$$\sin^2\theta_{12} = \frac{1 - 3\sin^2\theta_{13}}{3(1-\sin^2\theta_{13})}$$

$$\delta_{CP} = \arg\left(\frac{c^2}{2}e^{-i\alpha} - \frac{s^2}{3}e^{i\alpha}\right).$$

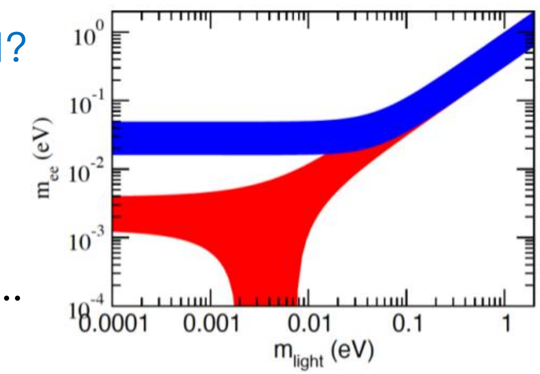
Juno finally mission: neutrino mass hirarchies: NH or IH another ~ 5 years!?



$$T^{0\nu}_{1/2} > 1.8 \times 10^{26}\ \mathrm{yr,\ at\ 90\%\ CL}$$

Compatible with inverted hierarchy. Good by neutrino–less double beta decay measurement!

DUNE and hyperK: CP violation. Another N ~ 8 years1?



Absolute neutrino mass Katrine and cosmology

$$m^{\mathrm{eff}}_{\nu_e} < 0.8\ \mathrm{eV}$$

Neutrinoless double beta decays: PandaX XT, CDEX….

A long time to wait!!

Theory? Later

Theory efforts to reduce model parameters

SM has many free parameters. Possible to reduce them?

Extensions of SM usually introduce more paramters in the model!

SUSY, Multi-Higgs, New symmetries, usually, introduce more parameters (some of them may reduce the parameter in certain sectors)...

Unification is one wayto try: Unify forces - reduce gauge couplings, Unify representation - reduce Yukawa coupling, relate masses of particles and etc...

Have more particles with higher masses scale than electroweak scale... but a progress for us looking at electroweak scale physics.

Examples: SO(10)

Gauge boson in 45 representation, Fermions in 16, Higgs fields 10 and 120, anti-126, 210…

$10 \to 5 + \bar{5}$

$16 \to 10 + \bar{5} + 1$

$45 \to 24 + 10 + \overline{10} + 1$

$54 \to 15 + \overline{15} + 24$

$120 \to 5 + \bar{5} + 10 + \overline{10} + 45 + \overline{45}$

$126 \to 1 + \bar{5} + 10 + \overline{15} + 45 + \overline{50}$

$210 \to 1 + 5 + \bar{5} + 10 + \overline{10} + 24 + 40 + \overline{40} + 75$

$$16 \Rightarrow 1_F = \nu^c + \mathbf{\bar{5}}_F = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix} + \mathbf{10}_F = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e_R \\ -d_1 & -d_2 & -d_3 & -e_R & 0 \end{pmatrix}$$

SO(10) Predictions

$$16_F(Y_{10}10_H + Y_{\overline{126}}\overline{126}_H + Y_{120}120_H)16_F$$

Minimal SO(10) Model without 120

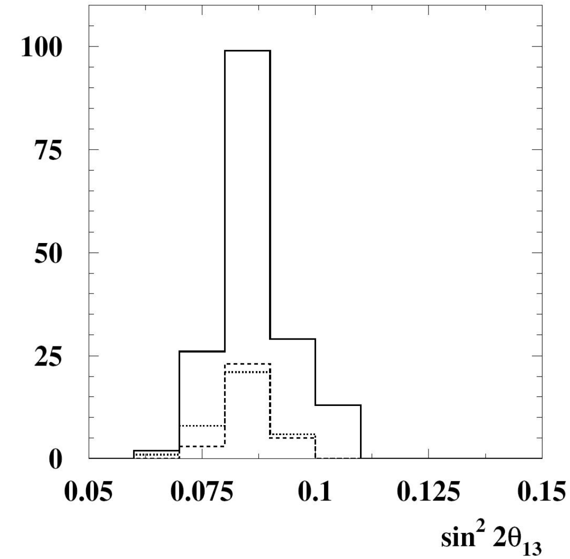
$$\mathcal{L}_{\text{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa_u' Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa_d' Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa_u' Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa_d' Y_{126} \end{aligned}$$

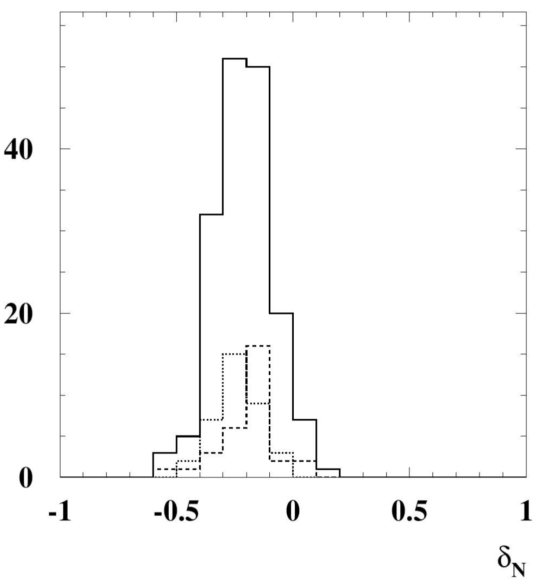
$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle Y_{126} \end{aligned}$$

Model has only 11 real parameters plus 7 phases



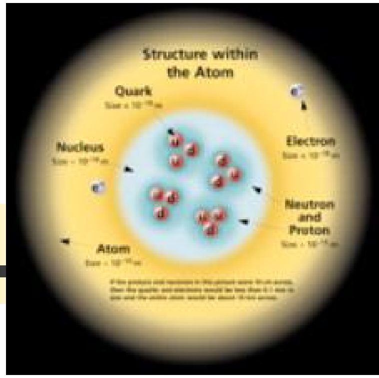
Good prediction for θ_{13}

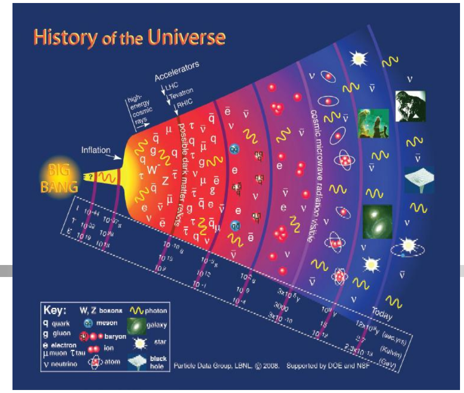
δ Away from $-\pi/2$!!! Tobe tested!!

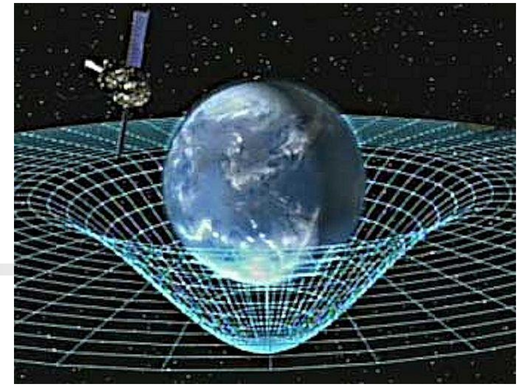


Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac,
Okada (2004)
Aulakh et al (2004)
Bertolini, Frigerio, Malinsky (2004
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)
Jushipura, Patel (2011).

Flavor of our Universe: The SM of Cosmology







At large scale of universe - gravity! Newton equation: F = - $G\frac{m_1 m_2}{r^2}$

In general relativity. Matter determines space-time: $ds^2 = g_{\mu\nu}dx^\mu dx^\nu$

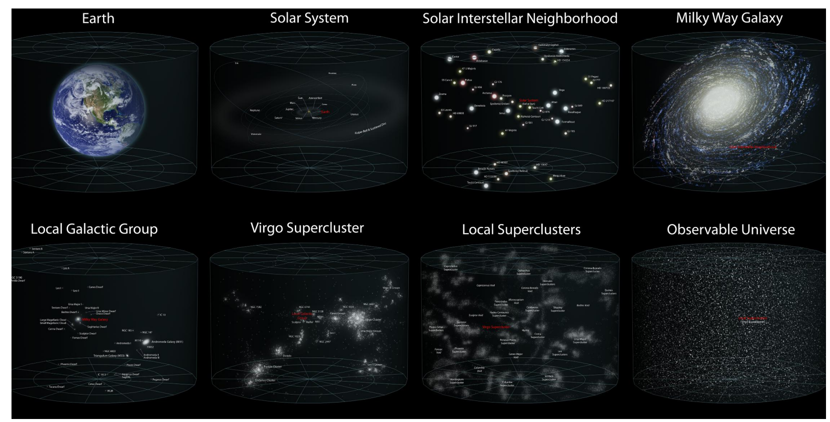
(Minkovski spacetime: $g_{00}=1, g_{ii} = -1$, others =0)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein equation

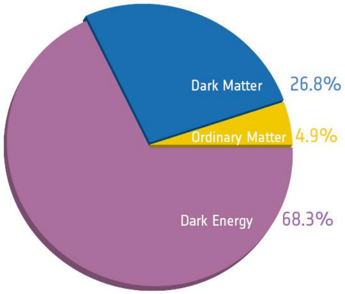
$G_{\mu\nu}$ – space-time signature

$T_{\mu\nu}$ – energy-momentum tensor of matter:
radiation, matter, dark matter, dark energy, and ...

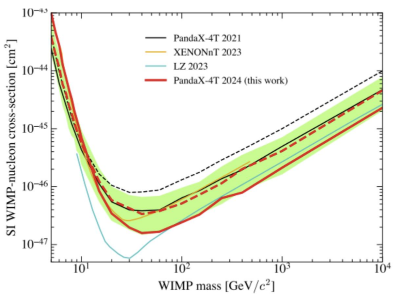


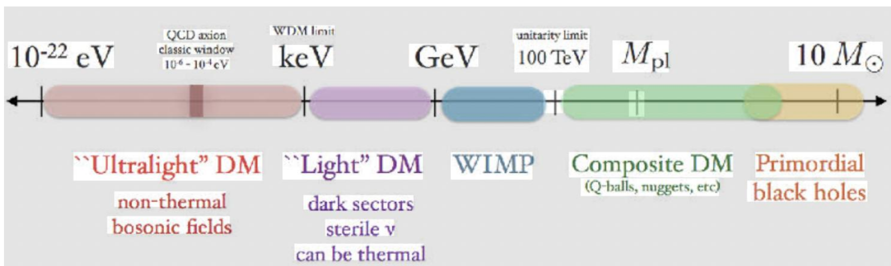
Homogenous and isotropic accelerately expanding Universe at large scales

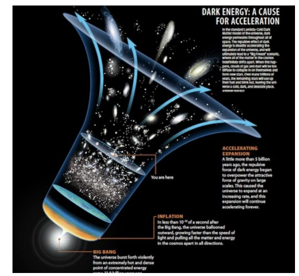
Flavor of our Universe

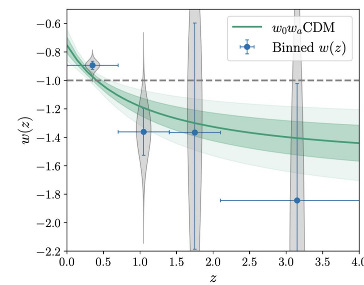


There are more flavors than fundamental particles we know from laboratory in our Universe, the dark matter and dark energy!



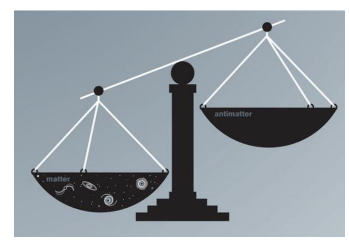






Dark matter and dark energy all gravitationaly felt, not direct detection yet!
These and elecmentary particles all affect the evolution of our Universe.
Cannot be separated!

Why our Universe has more matter than ani-matter?
The baryon number asymmetry problem!



2. Flavor physics and CP violation

Flavors: describe several copies of the same gauge representations

light flavors u, d, s and heavy flavors, c, b, t

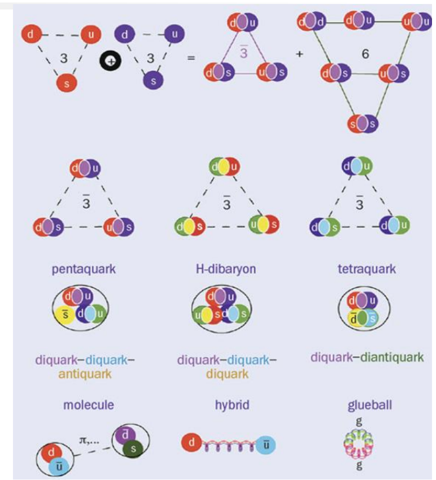
Flavor physics: the study of interactions that govern flavors.

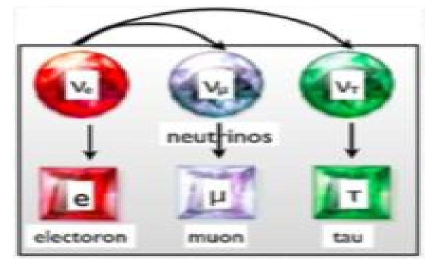
Electromagnetic interaction light, g-2 and flavor diagonal ...

Strong interaction gorverns hadron physics, color confinement

- key to spectroscopy...

Weak interaction one type of flavor change to another type





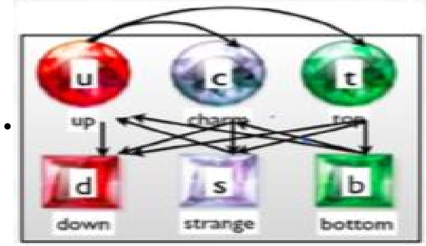
CP symmetry: C-charge conjugation and P-space parity.

Last year 60 years of CPV! (Cronin and Fitch)

This year 70 years of parity violation (TD Lee and CN Yang)

Strong and electromagnetism interactions respect these symmetries.

Weak interaction violates (breaks) these symmetries.



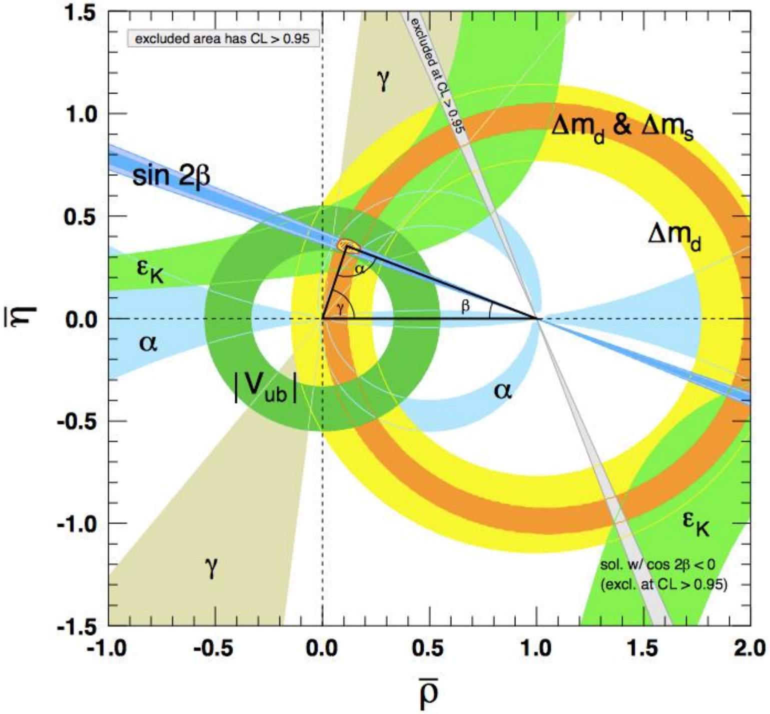
The mis-match of weak and mass eigen-state bases lead to generation mixing and CP violation (Kobayshi and Maskawa).

)

Status of Quark and Lepton Mixing

Quark Mixing — PDG — Neutrino Mixing

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

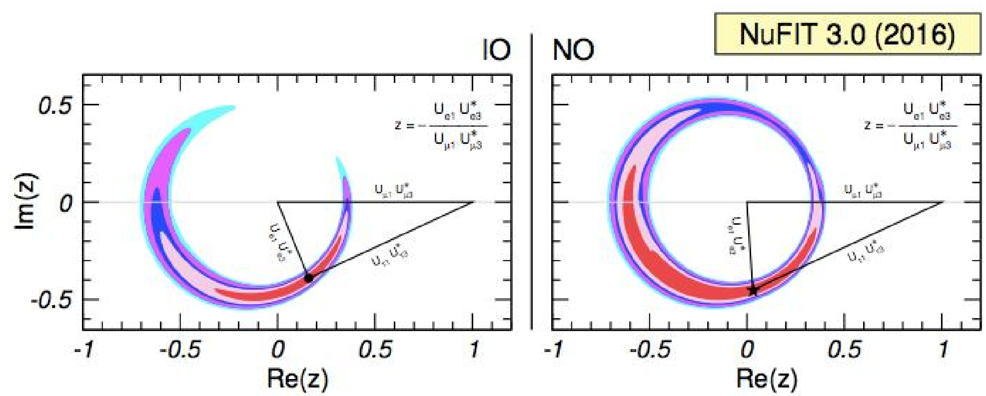


$$\lambda = 0.22500 \pm 0.00067\,, \qquad A = 0.826^{+0.018}_{-0.015}\,,$$
$$\bar{\rho} = 0.159 \pm 0.010\,, \qquad \bar{\eta} = 0.348 \pm 0.010\,.$$

$$\sin\theta_{12} = 0.22500 \pm 0.00067\,, \qquad \sin\theta_{13} = 0.00369 \pm 0.00011\,,$$
$$\sin\theta_{23} = 0.04182^{+0.00085}_{-0.00074}\,, \qquad \delta = 1.144 \pm 0.027\,.$$

$\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m^2_{31} - \Delta m^2_{21}/2 > 0$, if $m_1 < m_2 < m_3$ and $\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))



Why they mix the pattern shown above?

A large number of CP violating observables measured

Besides the original K-antiK mixing, varification of unitarity triangle

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.154 \pm 0.029)\%$$

$$\Lambda_b^0 \to p\pi^+K^-\pi^- \qquad A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = (2.45 \pm 0.46 \pm 0.10)\%.$$

$A_{CP}(B^0 \to K^+\pi^-) = -0.0834 \pm 0.0032$

$A_{CP}(B^0 \to K^*(892)^+\pi^-) = -0.27 \pm 0.04$

$S_{D^{*-}D^+}(B^0 \to D^*(2010)^- D^+) = -0.83 \pm 0.09$

$S_{D^{*+}D^-}(B^0 \to D^*(2010)^+ D^-) = -0.80 \pm 0.09$

$S_+(B^0 \to D^{*+}D^{*-}) = -0.73 \pm 0.09$

$S_{D^+D^-}(B^0 \to D^+D^-) = -0.76^{+0.15}_{-0.13}$ (S = 1.2)

$S(B^0 \to J/\psi(1S)\rho^0) = -0.66^{+0.16}_{-0.12}$

$S_{D^{(*)}_{CP}h^0}(B^0 \to D^{(*)}_{CP}h^0) = -0.66 \pm 0.12$

$S_{\eta' K^0}(B^0 \to \eta' K^0) = 0.63 \pm 0.06$

$S_{K^+K^-K^0_S}(B^0 \to K^+K^-K^0_S \text{ nonresonant}) = -0.66 \pm 0.11$

$S_{K^+K^-K^0_S}(B^0 \to K^+K^-K^0_S \text{ inclusive}) = -0.65 \pm 0.12$

$S_{\phi K^0_S}(B^0 \to \phi K^0_S) = 0.59 \pm 0.14$

$C_{\pi\pi}(B^0 \to \pi^+\pi^-) = -0.314 \pm 0.030$

$S_{\pi\pi}(B^0 \to \pi^+\pi^-) = -0.670 \pm 0.030$

$\Delta C_{\rho\pi}(B^0 \to \rho^+\pi^-) = 0.27 \pm 0.06$

$S_{\eta_c K^0_S}(B^0 \to \eta_c K^0_S) = 0.93 \pm 0.17$

$\sin(2\beta) = 0.699 \pm 0.017$

$S_{J/\psi(nS)K^0}(B^0 \to J/\psi(nS)K^0) = 0.701 \pm 0.017$

$S_{\chi_{c1}K^0_S}(B^0 \to \chi_{c1}K^0_S) = 0.63 \pm 0.10$

$\sin(2\beta_{\rm eff})(B^0 \to K^+K^-K^0_S) = 0.77^{+0.13}_{-0.12}$

$\alpha = (85.2^{+4.8}_{-4.3})^\circ$

$A_{CP}(B_s \to \pi^+K^-) = 0.224 \pm 0.012$

$A_{CP}(B^+ \to D_{CP(+1)}K^+) = 0.132 \pm 0.015$ (S = 1.8)

$A_{ADS}(B^+ \to DK^+) = -0.451 \pm 0.026$

$A_{ADS}(B^+ \to D\pi^+) = 0.129 \pm 0.014$

$A_{ADS}(B^+ \to D^*(D\gamma)K^+) = -0.6 \pm 1.3$

$A_{ADS}(B^+ \to D^*(D\pi^0)K^+) = 0.72 \pm 0.29$

$A_{CP}(B^+ \to \pi^+\pi^-\pi^+) = 0.057 \pm 0.013$

$A_{CP}(B^+ \to \rho^0K^+) = 0.37 \pm 0.10$

$A_{CP}(B^+ \to K^+K^-\pi^+) = -0.122 \pm 0.021$

$A_{CP}(B^+ \to K^+K^-K^+) = -0.033 \pm 0.008$

$\gamma = (65.9^{+3.3}_{-3.5})^\circ$

$r_B(B^+ \to D^0K^+) = 0.0994 \pm 0.0026$

$\delta_B(B^+ \to D^0K^+) = (127.7^{+3.6}_{-3.9})^\circ$

$r_B(B^+ \to D^0K^{*+}) = 0.101^{+0.016}_{-0.034}$

$\delta_B(B^+ \to D^0K^{*+}) = (48^{+59}_{-16})^\circ$

$r_B(B^+ \to D^{*0}K^+) = 0.104^{+0.013}_{-0.014}$

$\delta_B(B^+ \to D^{*0}K^+) = (314.8^{+7.9}_{-9.9})^\circ$

Some interesting results

SU(3) symmetry predicts

$$A(\bar{B}^0 \to K^-\pi^+) = V_{ub}V_{us}^*T + V_{tb}V_{ts}^*P\,,\quad A(B^0 \to K^+\pi^-) = V_{ub}^*V_{us}T + V_{tb}^*V_{ts}P\,,$$
$$A(\bar{B}_s^0 \to K^+\pi^-) = V_{ub}V_{ud}^*T + V_{tb}V_{td}^*P\,,\quad A(B_s^0 \to K^-\pi^+) = V_{ub}^*V_{ud}T + V_{tb}^*V_{td}P\,.$$

$$\frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + r_c \frac{Br(B_s^0 \to K^-\pi^+)\tau_{B^0}}{Br(B^0 \to K^+\pi^-)\tau_{B_s^0}} = 0\,.$$

In SU(3) limit, $r_c = 1$. Data gives: $r_c = 1.26 \pm 0.18$

SU(3) is a good approximate symmetry. Deshpande and He, PRL75(1995)1703; He, EPJC9(1999)443; He, Li, Lin, JHEP08(2013)065.

C_f type: $D \to K^+K^-$, $\pi^+\pi^-$ $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.154 \pm 0.029)\%$

LHCb measurement. Unexpected large!! Short distance contributions are small

Long distance strong interaction effects important at Charm scale.

SM ~ $2*10^{-4}$ need new physics (Chala, Lenz, Rusov, Scholtz, JHEP07(2019) 161)

Global fit for D -> PP decays, can accommodate

C.W. Chiang and H.Y. Cheng, PRD86(2012) 034036; HN Li, CD Lu, FS Yu, PRD86 (2012)036012.

Cannot be sure if SM is in conflict with data. Room for new physics.

The first CPV in baryon decay $\Lambda_b^0 \to p\pi^+K^-\pi^-$

congratulations to LHCb team!

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = (2.45 \pm 0.46 \pm 0.10)\%.$$

Observation of charge–parity symmetry breaking in baryon decays

LHCb Collaboration • Roel Aaij (Nikhef, Amsterdam) et al. (Mar 21, 2025)

Published in: *Nature* 643 (2025) 8074, 1223-1228 • e-Print: 2503.16954 [hep-ex]

LHCb paper has 58 citations so far!

Theoretical understanding: difficulty, multi hadron final states!

Can be partially tested by flavor SU(3) symmetry!

PHYSICAL REVIEW D **112,** L111302 (2025)

Large CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and its U-spin partner decays

Xiao-Gang He,* Chia-Wei Liu,† and Jusak Tandean‡

The LHCb Collaboration has recently found a large CP-violating rate asymmetry in the b-baryon decay $\Lambda_b^0 \to pK^-\pi^+\pi^-$. This is the first observation of CP violation in baryon processes, opening a new window to test its standard model (SM) origin. Many more baryon decays are expected to exhibit observable signals of CP violation. We show that there also exists large CP violation in the U-spin partner decay mode, $\Xi_b^0 \to \Sigma^+\pi^-K^+K^-$, with rate asymmetry $A_{CP}(\Xi_b^0 \to \Sigma^+\pi^-K^+K^-) = -A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-)\frac{\mathrm{Br}(\Lambda_b^0 \to pK^-\pi^+\pi^-)}{\mathrm{Br}(\Xi_b^0 \to \Sigma^+\pi^-K^+K^-)}\frac{\tau_{\Xi_b}}{\tau_{\Lambda_b}}$ in the U-spin symmetry limit. By neglecting a subleading contribution in the amplitudes, $A_{CP}(\Lambda_b^0 \to p\pi^+\pi^-\pi^-) = -(12 \pm 6)\%$. These predictions can be tested in the near future.

arXiv > hep-ex > arXiv:2509.16103

High Energy Physics – Experiment

[Submitted on 19 Sep 2025]

First evidence of CP violation in beauty baryon to charmonium decays

$$\Delta A_{CP} = A_{CP}^{dir}(\Lambda_b \to p\pi^- J/\psi) - A_{CP}^{dir}(\Lambda_b \to pK^- J/\psi)$$
$$= (4.31 \pm 1.06 \pm 0.28)\% \,, \qquad (1)$$

How to obtain information from the above? Again flavor SU(3) symmetry comes to help:e-Print: 2511.06008

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to p\pi^- J/\psi) - A_{CP}(\Lambda_b^0 \to pK^- J/\psi)$$
$$= A_{CP}(\Lambda_b^0 \to n\pi^0 J/\psi) - A_{CP}(\Lambda_b^0 \to nK_{S,L} J/\psi)$$
$$= A_{CP}(\Xi_b^- \to \Xi^- K_{S,L} J/\psi) - A_{CP}(\Lambda_b^0 \to nK_{S,L} J/\psi) \,.$$

CPV in other baryon systems: Charmed and Hyperon baryons

CP violation in charmed baryons have not discovered. Surprises as what happen in CP violation charmed messon decay? May be!

Science Bulletin 70 (2025) 2598–2603

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Article

Large CP violation in charmed baryon decays

Xiao-Gang He *, Chia-Wei Liu *

PHYSICAL REVIEW D **109,** L071302 (2024)

Letter

Complete determination of $SU(3)_F$ amplitudes and strong phase in $\Lambda_c^+ \to \Xi^0 K^+$

Chao-Qiang Geng,[1,*] Xiao-Gang He,[2,3,†] Xiang-Nan Jin,[1,‡] Chia-Wei Liu,[2,§] and Chang Yang[2,∥]

Deacay amplitudes can be completely determined by data

Also JHEP 09(2025)193

The $\mathcal{B}$, A_{CP}, and A_{CP}^{α} are presented in units of 10^{-3}. The upper rows of A_{CP} and A_{CP}^{α} are obtained by taking $h_3 = 0$, while the lower rows are obtained through the FSR mechanism. The uncertainties are quoted in the same manner as Table 1. There may be some $SU(3)_F$ breaking effects that affect the results on the order of 10^{-1}, as found in the hyperons.

Channels	$\mathcal{B}$	A_{CP}	A_{CP}^{α}	Channels	$\mathcal{B}$	A_{CP}	A_{CP}^{α}
$\Lambda_c^+ \to p\pi^0$	0.18(2)	−0.01(7)	−0.15(13)	$\Xi_c^0 \to \Sigma^+\pi^-$	0.26(2)	0	0
		0.01(15)(45)	0.55(20)(61)			0.71(15)(6)	−1.83(10)(15)
$\Lambda_c^+ \to n\pi^+$	0.68(6)	0.0(1)	0.03(2)	$\Xi_c^0 \to \Sigma^0\pi^0$	0.34(3)	−0.02(4)	0.01(1)
		−0.02(7)(28)	0.30(13)(41)			0.44(24)(17)	−0.43(31)(16)
$\Lambda_c^+ \to \Lambda K^+$	0.62(3)	0.00(2)	0.03(2)	$\Xi_c^0 \to \Sigma^-\pi^+$	1.76(5)	0.01(1)	−0.01(1)
		−0.15(13)(9)	0.50(9)(21)			0.12(6)(2)	−0.22(5)(21)
$\Xi_c^+ \to \Sigma^+\pi^0$	2.69(14)	−0.02(6)	0.07(4)	$\Xi_c^0 \to \Xi^0 K_{S/L}$	0.38(1)	0	0
		0.05(7)(8)	−0.23(3)(15)			0.18(3)(5)	−0.38(2)(11)
$\Xi_c^+ \to \Sigma^0\pi^+$	3.14(10)	0.00(1)	−0.02(1)	$\Xi_c^0 \to \Xi^- K^+$	1.26(4)	0.00(1)	0.01(1)
		0.05(8)(7)	−0.24(6)(13)			−0.12(5)(2)	0.21(4)(2)
$\Xi_c^+ \to \Xi^0 K^+$	1.30(10)	0.00(0)	−0.02(1)	$\Xi_c^0 \to pK^-$	0.31(2)	0	0
		0.01(6)(17)	−0.23(9)(52)			−0.73(18)(6)	1.74(11)(14)
$\Xi_c^+ \to \Lambda\pi^+$	0.18(3)	−0.01(2)	0.0(0)	$\Xi_c^0 \to nK_{S/L}$	0.86(3)	0	0
		−0.31(21)(13)	0.96(25)(44)			−0.14(3)(4)	0.27(2)(7)
$\Xi_c^+ \to pK_s$	1.55(7)	0	0	$\Xi_c^0 \to \Lambda\pi^0$	0.06(2)	0.02(3)	0.0(1)
		−0.13(3)(4)	0.22(3)(7)			−0.12(18)(10)	0.69(8)(43)

Channels	$F^{\rm SCS}$	F^b
$\Lambda_c^+ \to \Sigma^+ K_S$	$\frac{\sqrt{2}(\tilde f^b-\tilde f^d)}{2}$	$\frac{\sqrt{2}\tilde f^b_{\bf 3}}{2}$
$\Lambda_c^+ \to \Sigma^0 K^+$	$\frac{\sqrt{2}(\tilde f^b-\tilde f^d)}{2}$	$\frac{\sqrt{2}\tilde f^b_{\bf 3}}{2}$
$\Lambda_c^+ \to p\pi^0$	$\frac{\sqrt{2}(\tilde f^c+\tilde f^d+\tilde f^e)}{2}$	$\frac{\sqrt{2}\cdot(4\tilde f^d_{\bf 3}+3\tilde f^e)}{8}$
$\Lambda_c^+ \to p\eta$	$\frac{\sqrt{6}c_\phi(-2\tilde f^b+\tilde f^c-\tilde f^d-3\tilde f^e)}{6}+\frac{\sqrt{3}s_\phi(-3\tilde f^a)}{3}$	$\sqrt{6}c_\phi\left(-\frac{\tilde f^b_{\bf 3}}{3}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)+\frac{\sqrt{3}s_\phi(-3\tilde f^a_{\bf 3})}{3}$
$\Lambda_c^+ \to p\eta'$	$\frac{\sqrt{6}s_\phi(-2\tilde f^b+\tilde f^c-\tilde f^d-3\tilde f^e)}{6}-\frac{\sqrt{3}c_\phi(-3\tilde f^a)}{3}$	$\sqrt{6}s_\phi\left(-\frac{\tilde f^b_{\bf 3}}{3}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)-\frac{\sqrt{3}c_\phi(-3\tilde f^a_{\bf 3})}{3}$
$\Lambda_c^+ \to n\pi^+$	$\tilde f^c+\tilde f^d-\tilde f^e$	$\tilde f^d_{\bf 3}-\frac{\tilde f^e}{4}$
$\Lambda_c^+ \to \Lambda K^+$	$\frac{\sqrt{6}(\tilde f^b-2\tilde f^c+\tilde f^d-2\tilde f^e)}{6}$	$\frac{\sqrt{6}\cdot(2\tilde f^b_{\bf 3}-4\tilde f^d_{\bf 3}+\tilde f^e)}{12}$
$\Xi_c^+ \to \Sigma^+\pi^0$	$\frac{\sqrt{2}(\tilde f^b-\tilde f^c+\tilde f^e)}{2}$	$\frac{\sqrt{2}(-4\tilde f^b_{\bf 3}+4\tilde f^d_{\bf 3}+3\tilde f^e)}{8}$
$\Xi_c^+ \to \Sigma^+\eta$	$\frac{\sqrt{6}c_\phi(-\tilde f^b-\tilde f^c-2\tilde f^d-3\tilde f^e)}{6}+\frac{\sqrt{3}s_\phi(3\tilde f^a)}{3}$	$\sqrt{6}c_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)+\frac{\sqrt{3}s_\phi(-3\tilde f^a_{\bf 3})}{3}$
$\Xi_c^+ \to \Sigma^+\eta'$	$\frac{\sqrt{6}s_\phi(-\tilde f^b-\tilde f^c-2\tilde f^d-3\tilde f^e)}{6}-\frac{\sqrt{3}c_\phi(3\tilde f^a)}{3}$	$\sqrt{6}s_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)-\frac{\sqrt{3}c_\phi(-3\tilde f^a_{\bf 3})}{3}$
$\Xi_c^+ \to \Sigma^0\pi^+$	$\frac{\sqrt{2}(-\tilde f^b+\tilde f^c+\tilde f^e)}{2}$	$\frac{\sqrt{2}\cdot(4\tilde f^b_{\bf 3}-4\tilde f^d_{\bf 3}+\tilde f^e)}{8}$
$\Xi_c^+ \to \Xi^0 K^+$	$-\tilde f^c-\tilde f^d+\tilde f^e$	$\tilde f^d_{\bf 3}-\frac{\tilde f^e}{4}$
$\Xi_c^+ \to pK_S$	$\frac{\sqrt{2}(\tilde f^b-\tilde f^d)}{2}$	$-\frac{\sqrt{2}\tilde f^b_{\bf 3}}{2}$
$\Xi_c^+ \to \Lambda\pi^+$	$\frac{\sqrt{6}(-\tilde f^b-\tilde f^c+2\tilde f^d-\tilde f^e)}{6}$	$\frac{\sqrt{6}\cdot(4\tilde f^b_{\bf 3}+4\tilde f^d_{\bf 3}-\tilde f^e)}{24}$
$\Xi_c^0 \to \Sigma^+\pi^-$	$\tilde f^c$	$\tilde f^b_{\bf 3}+\tilde f^c_{\bf 3}$
$\Xi_c^0 \to \Sigma^0\pi^0$	$\frac{\tilde f^b}{2}+\frac{\tilde f^c}{2}+\frac{\tilde f^e}{2}$	$\frac{\tilde f^b_{\bf 3}}{2}+\tilde f^c_{\bf 3}+\frac{\tilde f^d_{\bf 3}}{2}+\frac{3\tilde f^e}{8}$
$\Xi_c^0 \to \Sigma^0\eta$	$\frac{\sqrt{3}c_\phi(-\tilde f^b-\tilde f^c-2\tilde f^d-3\tilde f^e)}{6}+\frac{\sqrt{6}s_\phi(3\tilde f^a)}{6}$	$\sqrt{3}c_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)+\frac{\sqrt{6}s_\phi(-3\tilde f^a_{\bf 3})}{6}$
$\Xi_c^0 \to \Sigma^0\eta'$	$\frac{\sqrt{3}s_\phi(-\tilde f^b-\tilde f^c-2\tilde f^d-3\tilde f^e)}{6}-\frac{\sqrt{6}c_\phi(3\tilde f^a)}{6}$	$\sqrt{3}s_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)-\frac{\sqrt{6}c_\phi(-3\tilde f^a_{\bf 3})}{6}$
$\Xi_c^0 \to \Sigma^-\pi^+$	$\tilde f^b-\tilde f^e$	$\tilde f^c_{\bf 3}+\tilde f^d_{\bf 3}-\frac{\tilde f^e}{4}$
$\Xi_c^0 \to \Xi^0 K_S$	$\frac{\sqrt{2}(-\tilde f^b+\tilde f^c+\tilde f^d)}{2}$	$\frac{\sqrt{2}\tilde f^c_{\bf 3}}{2}$
$\Xi_c^0 \to \Xi^- K^+$	$-\tilde f^b+\tilde f^e$	$\tilde f^c_{\bf 3}+\tilde f^d_{\bf 3}-\frac{\tilde f^e}{4}$
$\Xi_c^0 \to pK^-$	$-\tilde f^c$	$\tilde f^b_{\bf 3}+\tilde f^c_{\bf 3}$
$\Xi_c^0 \to nK_S$	$\frac{\sqrt{2}(-\tilde f^b+\tilde f^c+\tilde f^d)}{2}$	$-\frac{\sqrt{2}\tilde f^c_{\bf 3}}{2}$
$\Xi_c^0 \to \Lambda\pi^0$	$\frac{\sqrt{3}(-\tilde f^b-\tilde f^c+2\tilde f^d+\tilde f^e)}{6}$	$\sqrt{3}\left(\frac{\tilde f^b_{\bf 3}}{6}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)$
$\Xi_c^0 \to \Lambda\eta$	$c_\phi\left(-\frac{\tilde f^b}{2}-\frac{\tilde f^c}{2}-\frac{\tilde f^e}{2}\right)+\frac{\sqrt{2}s_\phi(-3\tilde f^a)}{2}$	$c_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\tilde f^c_{\bf 3}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)+\frac{\sqrt{2}s_\phi(-3\tilde f^a_{\bf 3})}{6}$
$\Xi_c^0 \to \Lambda\eta'$	$s_\phi\left(-\frac{\tilde f^b}{2}-\frac{\tilde f^c}{2}-\frac{\tilde f^e}{2}\right)-\frac{\sqrt{2}c_\phi(-3\tilde f^a)}{2}$	$s_\phi\left(\frac{\tilde f^b_{\bf 3}}{6}+\tilde f^c_{\bf 3}+\frac{\tilde f^d_{\bf 3}}{6}+\frac{\tilde f^e}{8}\right)-\frac{\sqrt{2}c_\phi(-3\tilde f^a_{\bf 3})}{6}$

CPV can be as large as a few times 10^{-3} !!!

Using data, tree and penguin contributions can be separated!

Deconding the amplitude pair with distinctive CPV phases in charmed baryon decays, arXiv: 2601.08502

CPV in hyperon decays　　a long history! Great Job done at BESIII

	Δ	A	B
$\Lambda^0 \to p\pi^-$	-5.4×10^{-7}	-0.5×10^{-4}	3.0×10^{-3}
$\Xi^- \to \Lambda^0\pi^-$	0	-0.7×10^{-4}	8.4×10^{-4}
$\Sigma^- \to n\pi^-$	0	1.6×10^{-4}	-1.2×10^{-2}
$\Sigma^+ \to p\pi^0$	-6.2×10^{-7}	-3.2×10^{-7}	-4.2×10^{-4}
$\Sigma^+ \to n\pi^+$	6.0×10^{-7}	-1.6×10^{-4}	-8.4×10^{-7}

Signals of {CP} Nonconservation in Hyperon Decay
John F. Donoghue (Massachusetts U., Amherst), Sandip Pakvasa (Hawaii U.).
Published in **Phys.Rev.Lett. 55 (1985) 162**

Hyperon decays and *CP* nonconservation

John F. Donoghue
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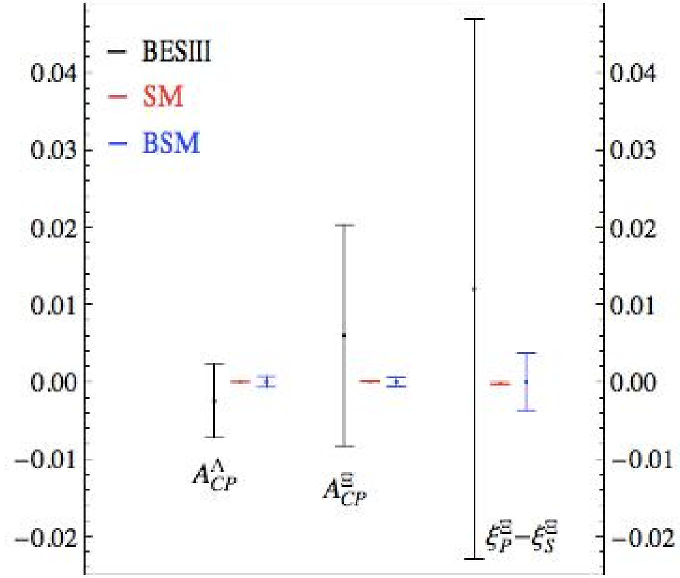
Xiao-Gang He and Sandip Pakvasa
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822
(Received 7 March 1986)

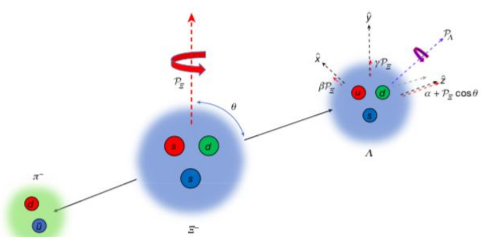
We study all modes of hyperon nonleptonic decay and consider the *CP*-odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of *CP* nonconservation.



$A_{\Xi\Lambda} = A_\Xi + A_\Lambda$　HyperCP (Femilab E871): $A_{\Xi\Lambda} = [-6.0 \pm 2.1(\text{stat}) \pm 2.0(\text{syst})] \times 10^{-4}$

Recent measurement from BESIII
(Nature 606(2022)64)

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \qquad B_{CP} = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$$



$$A^{\Xi}_{CP} = (6 \pm 13 \pm 6) \times 10^{-3},$$
$$B^{\Xi}_{CP} \simeq \xi^{\Xi}_P - \xi^{\Xi}_S = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2},$$
$$A^{\Lambda}_{CP} = (-4 \pm 12 \pm 9) \times 10^{-3}$$

So far not CP violation effects have been established in baryon decay!
STCF is our hope
Similar ideas can be used for c- and b-baryon decays.

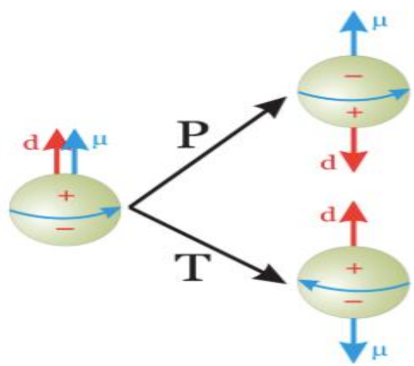
The EDM of a fundamental particle

Magnetic Dipole conserves P and T

$H_{mdm} = d_m \vec{S} \cdot \vec{B}$,

Under P: $\vec{B} \to \vec{B}$ and under T: $\vec{B} \to -\vec{B}$

Relativistic expression: $d_m \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$.

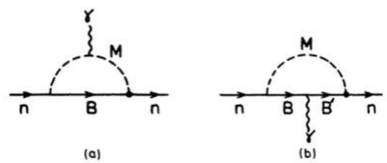


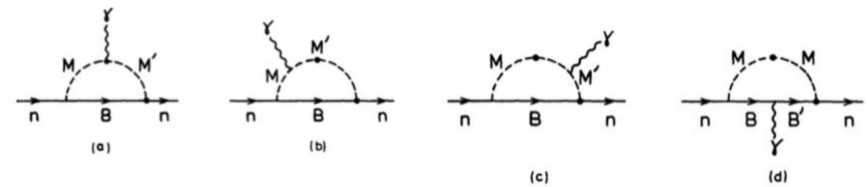
In KM model, quark EDM only generated at two electroweak and one strong loop level (3 loop effects)l, very small ~ 10^{-33} e.cm. (Shabalin, 1978, 1980)

In fact with two weak and one strong interaction vertices, EDM can also be generated!

(He, McKellar and Pakvasa, PLB197, 556(1987), J. Mod. Phys. A4, 5011(1989)

$$1.6 \times 10^{-31}\ \text{e.cm} \geq |D_n| \geq 1.4 \times 10^{-33}\ \text{e.cm}$$





Electron EDM is even smaller, generated at fourth loop level, $D_e < 10^{-38}$ecm

$$D_n \sim -3.8 \times 10^{-16} \theta \text{ ecm}$$

Including all SU(3) octet contributions:

$$2.5 \times 10^{-16} \theta ecm < |D_n| < 4.6 \times \theta ecm$$

Using data $|D_n| < 3 \times 10^{-27} ecm$, $|\theta| < 10^{-11}$!

Neutron $|D_n| < 1.8 \times 10^{-26}$ ecm,
electron $|D_e| < 1.1 \times 10^{-29}$ ecm

Why θ is small is the strong CP problem.

One of the best solution is the Axion model, in which θ is dynamically driven to zero!

A new test of CP violation for Hyperon production

a

X-G He, J-P Ma, B. Mckellar, PRD 47(1993) 1744; X-G He and J-P Ma, PLB839(2023)137834
Yong Du, X-G He, J-P Ma, X-Y Du, PRD 110(2024)076019

Testing of P and CP symmetries with $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

$$\mathcal{A}^\mu = \bar{u}(k_1)\left[\gamma^\mu F_V + \frac{i}{2m_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma_5 F_A + \sigma^{\mu\nu}q_\nu\gamma_5 H_T\right]v(k_2),$$

$$G_1^B = F_V^B + H_\sigma^B, \quad G_2^B = G_1^B - \frac{(k_1-k_2)^2}{4m_B^2}H_\sigma^B, \qquad H_T = \frac{2e}{3m_{J/\psi}^2}g_V d_\Lambda$$

$$\Lambda \to p + \pi \text{ or } \Lambda \to \bar{p} + \pi$$

$\hat{l}_p$, $l_{\bar{p}}$ and $\hat{k}$ momentum directions of p, $\bar{p}$ and Λ.

$$\mathcal{A}(\hat{\boldsymbol{l}}_b\cdot\hat{\boldsymbol{k}} + \hat{\boldsymbol{l}}_{\bar{b}}\cdot\hat{\boldsymbol{k}}) \equiv A_{\rm CPV}^{(1)} \simeq -\frac{4\alpha_B\beta}{3\mathcal{N}}E_c^3\,{\rm Im}\left(H_T G_1^* + y_m H_T G_2^*\right),$$

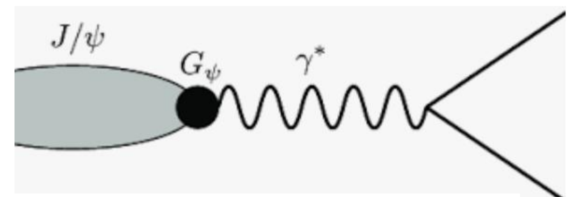
$$\mathcal{A}((\hat{\boldsymbol{l}}_b\times\hat{\boldsymbol{l}}_{\bar{b}})\cdot\hat{\boldsymbol{k}}) \equiv A_{\rm CPV}^{(2)} \simeq -\frac{8\alpha_B\bar{\alpha}}{9\mathcal{N}}\beta y_m E_c^3{\rm Re}\left(H_T G_2^*\right),$$

Electric ipole moment contribution to H_T

H_T is flavor conserving CP violating. It is extremely small in the SM. Beyond SM, it may be large. Consider now Λ edm contribution.

$$L_{edm} = -i\frac{d_\Lambda}{2}\Lambda\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu}$$

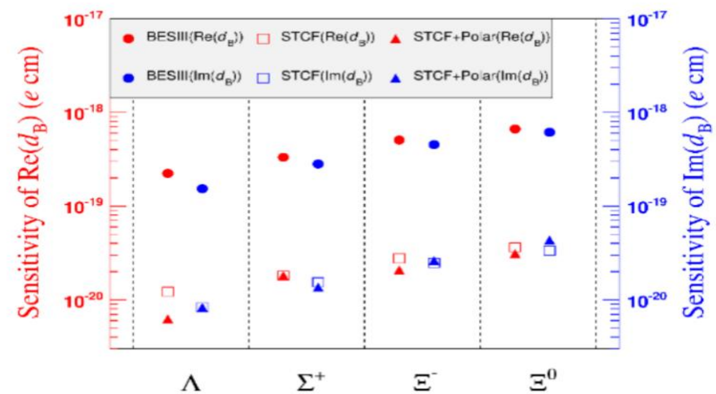
Exchange a photon: HT -> $\frac{ed_\Lambda}{s}\bar{e}\gamma^\mu e\Lambda\sigma_{\mu\nu}\gamma_5\Lambda q^\nu$



Lambda $|d_\Lambda| < 1.5 \times 10^{-16}$ ecm, Existing bound

$$Re(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e\ \text{cm},$$

$$Im(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e\ \text{cm}.$$



BESIII arXiv: 2506.19180

Xuelei Sun et al, arXiv: 2411.19469
HB Li group

Perturbative QCD calculation for EDM with non-zero q^2

KB Chen, XG He, JP Ma, XB Tong, PRL (2026), arXiv: 2509.22087

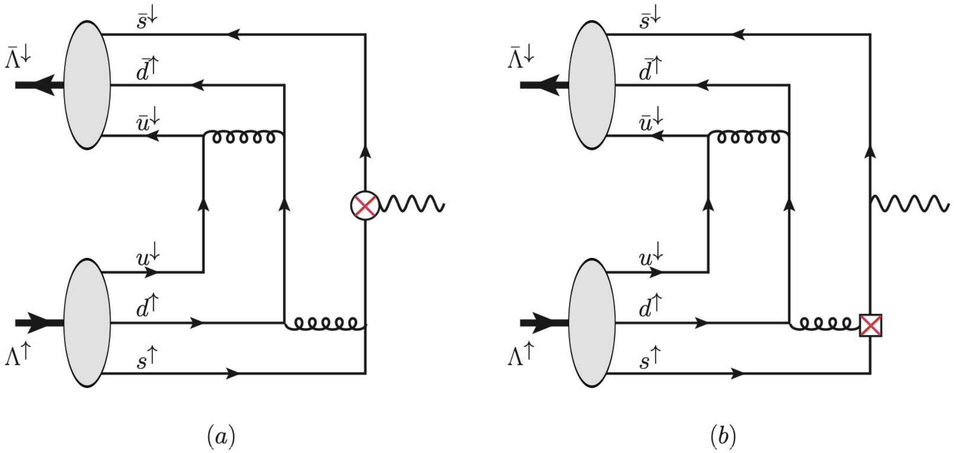


Figure 1: (a). A typical diagram for the contribution from the EDM d_s. The photon vertex with a cross-circle is the EDM vertex. (b). A typical diagram for the contribution from the CEDM $\tilde{d}_s$. The gluon vertex with a crossed square represents the CEDM vertex.

$$d_\Lambda = 5.29 \times 10^{-4} d_s + 4.61 \times 10^{-5}(d_u + d_d) + 6.21 \times 10^{-5} e\tilde{d}_s + 1.98 \times 10^{-5} e\tilde{d}_d - 2.14 \times 10^{-5} e\tilde{d}_u \; .$$

When q^2 not zero, experimental constraints are much stronger by a few order of magnitudes!

Tauon edm measurement at $e^+e^- \to \tau^+ \tau^-$

XG He, CW Liu, LP Ma and ZY Zou, JHEP 04 (2025) 001; XR Zhou group.

Use similar method replacing J/psi -> hyperon pairs by $\psi(2S) \to \tau^+ \tau^-$, or just $e^+e^- \to \gamma^* \to \tau^+ \tau^-$

STCF can reach a better resoltuion than current best bounds.

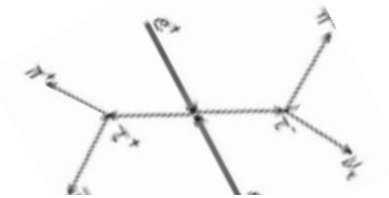
$$\mathrm{Re}(d_\tau) = (6.2 \pm 6.3) \times 10^{-18}\ e\,\mathrm{cm},$$

$$\mathrm{Im}(d_\tau) = (4.0 \pm 3.2) \times 10^{-18}\ e\,\mathrm{cm},$$

current bounds from BELLE II

Bell II can also use Upsilon(4S) to do similar things

$\tau(k) \to \pi(l) + \nu,\ \rho(l) + \nu$



For the the imaginary part, we have

$$\mathrm{Im}(d_\tau) = \frac{-e(3s+6m_\tau^2)}{4s\sqrt{s-4m_\tau^2}} \left(\frac{\langle \hat{l}_{h^-} \cdot \hat{k} \rangle}{\alpha_h} + \frac{\langle \hat{l}_{h'^+} \cdot \hat{k} \rangle}{\bar{\alpha}_{h'}} \right). \quad (6)$$

There are two different methods to extract the real part of the EDM from the distributions:

$$\mathrm{Re}(d_\tau)^a = e\frac{9}{4} \frac{s+2m_\tau^2}{\alpha_h \alpha_{h'} m_\tau \sqrt{s^2-4sm_\tau^2}} \langle (\hat{l}_- \times \hat{l}_+) \cdot \hat{k} \rangle , \quad (7)$$

and

$$\mathrm{Re}(d_\tau)^b = -e\frac{45}{4} \frac{(s+2m_\tau^2)\langle (\hat{p}\cdot\hat{k})(\hat{l}_- \times \hat{l}_+)\cdot\hat{p}\rangle}{\alpha_h \alpha_{h'} m_\tau (\sqrt{s}-2m_\tau)\sqrt{s-4m_\tau^2}} . \quad (8)$$

Table I. The precision of d_τ that may be achieved with $L\epsilon = 0.63\,\mathrm{ab}^{-1}$ is given in units of $10^{-18} e\,\mathrm{cm}$. The absolute value is defined as $\delta^2_{|d_\tau|}(D) = \delta_{\mathrm{Re}}(D)^2 + \delta_{\mathrm{Im}}(D)^2$, where D is in units of μm. The case $D = 0$ corresponds to situations where the τ-lepton momentum can be reconstructed with 100% accuracy which is shown only as a reference number.

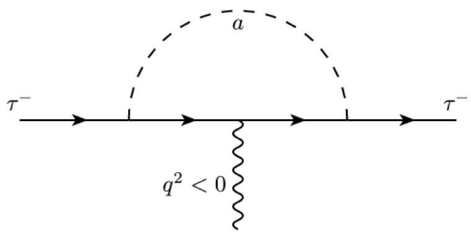
$\sqrt{s}$	$m_{\psi(2S)}$	4.2 GeV	4.9 GeV	5.6 GeV	6.3 GeV	7 GeV
δ_{Im}	3.5	1.8	1.4	1.3	1.3	1.4
$\delta_{\mathrm{Re}}(180)$	234	14.7	6.6	4.9	4.3	4.1
$\delta_{\mathrm{Re}}(130)$	82	9.4	5.0	4.0	3.7	3.6
$\delta_{\mathrm{Re}}(80)$	29	6.2	3.9	3.3	3.2	3.2
$\delta_{\mathrm{Re}}(30)$	11	4.4	3.2	2.9	2.9	3.0
$\delta_{\mathrm{Re}}(0)$	7.7	4.0	3.0	2.8	2.8	2.9
$\delta_{\|d_\tau\|}(80)$	30	6.5	4.1	3.6	3.5	3.5

Theoretical model study for tau EDM

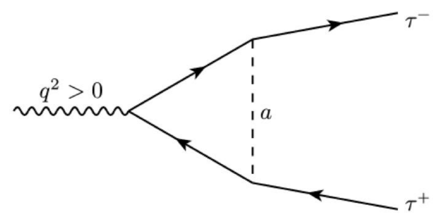
ZL Huang, XY Du, XG He, CW Liu, ZY Zou, arXiv:2510.23348

A light ALP example:

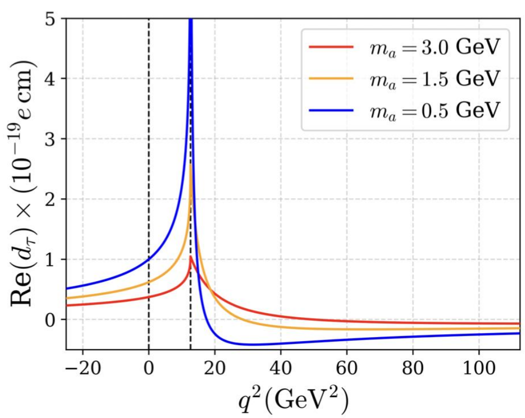
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \bar{\tau}(i\not{\partial} - m_\tau)\tau + a\,\bar{\tau}(a_a + i b_a \gamma_5)\tau,$$



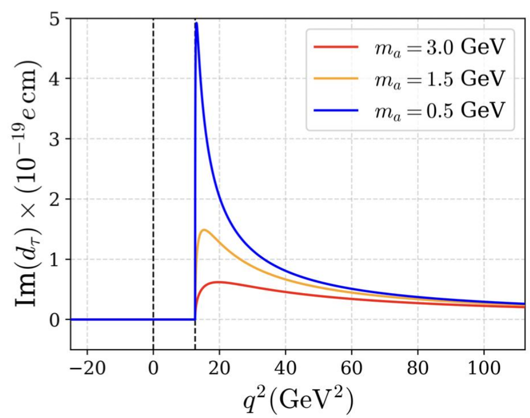
(a) spacelike



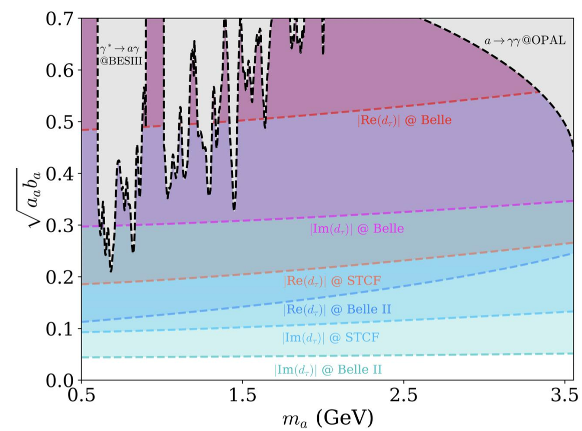
(b) timelike



(a) $\mathrm{Re}(d_\tau(q^2))$



(b) $\mathrm{Im}(d_\tau(q^2))$



3. Flavor physics and new physics beyond SM

Anomalies

CKM unitarity anomaly? $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$,

$|V_{ub}|^2 \sim 10^{-5}$ negligible, so usually study
$\Delta = |V_{ud}|^2 + |V_{us}|^2 - 1$

Zoom in superallowed 0+ -> 0+ nuclei transition and K -> π l ν show about 3σ level deviation

aeXiv:2208.11707

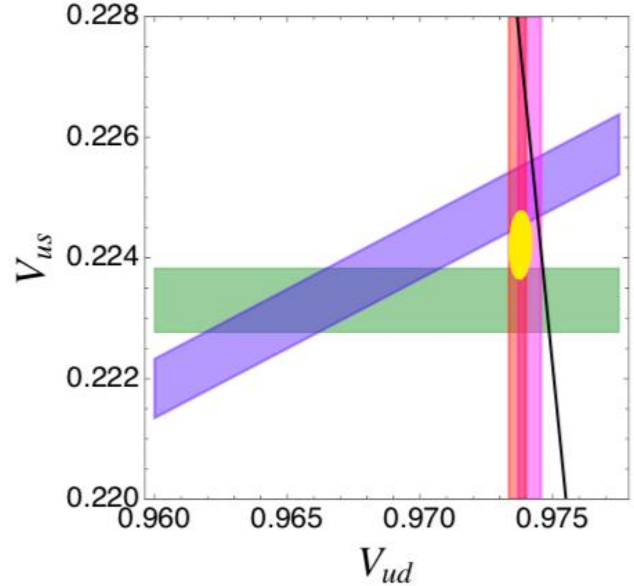
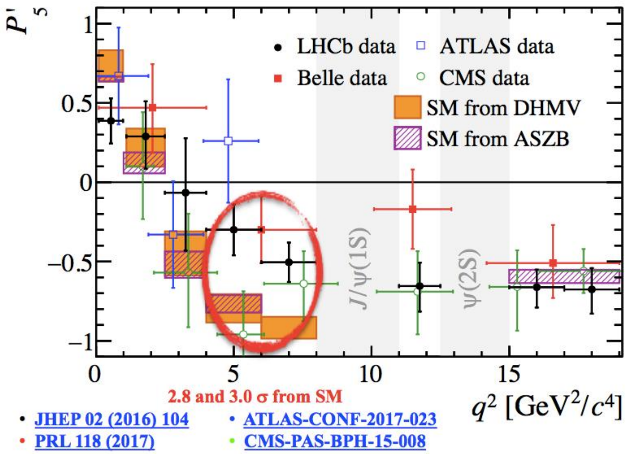


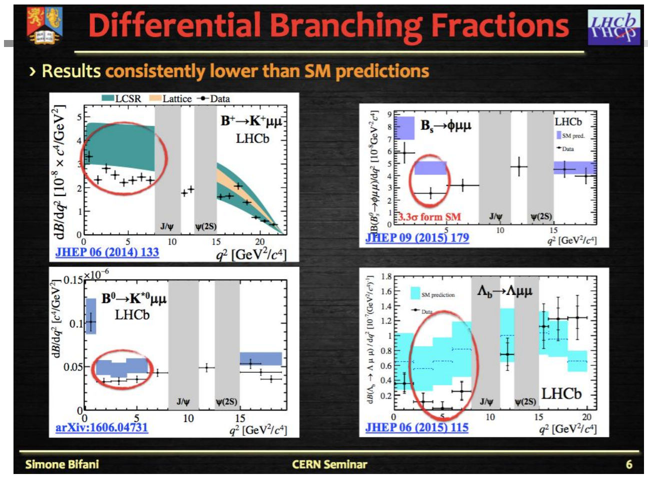
Figure 1: Constraints in the V_{ud}–V_{us} plane. The partially overlapping vertical bands correspond to $V_{ud}^{0^+\to0^+}$ (leftmost, red) and $V_{ud}^{n,\,\text{best}}$ (rightmost, violet). The horizontal band (green) corresponds to $V_{us}^{K_{\ell 3}}$. The diagonal band (blue) corresponds to $(V_{us}/V_{ud})_{K_{\ell 2}/\pi_{\ell 2}}$. The unitarity circle is denoted by the black solid line. The 68% C.L. ellipse from a fit to all four constraints is depicted in yellow ($V_{ud} = 0.97378(26)$, $V_{us} = 0.22422(36)$, $\chi^2/\text{dof} = 6.4/2$, p-value 4.1%), it deviates from the unitarity line by 2.8σ. Note that the significance tends to increase in case τ decays are included.

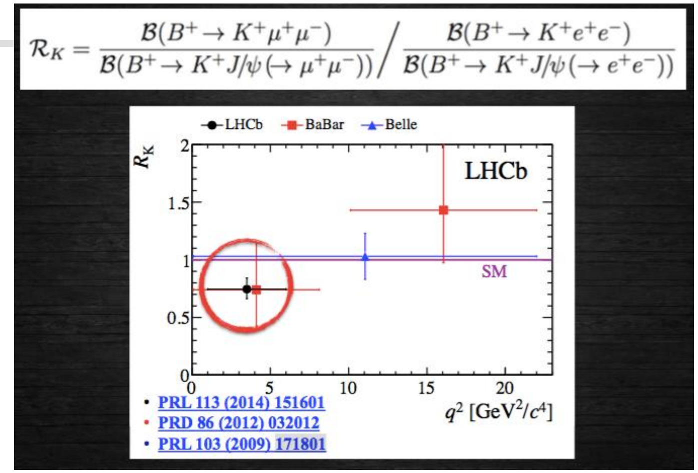
$\Delta^{(1)}_{\text{CKM}}$	$-0.00176(56)$	$-0.00173(55)$	$-0.00162(56)$	$-0.00185(56)$	$-0.00171(55)$	$-0.00151(56)$	$-0.00195(56)$
	-3.1σ	-3.1σ	-2.9σ	-3.3σ	-3.1σ	-2.7σ	-3.5σ

The $R_{K(*)}$ anomalies

Deviation used to be about 4σ







$$R_{K,K^*}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\ ^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\ ^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

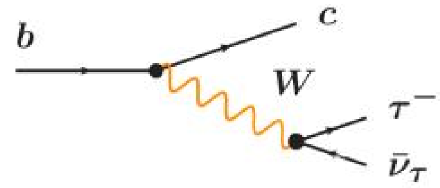
$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\ ^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\ ^{+0.027}_{-0.026}\,(\text{syst}), \end{cases}$$

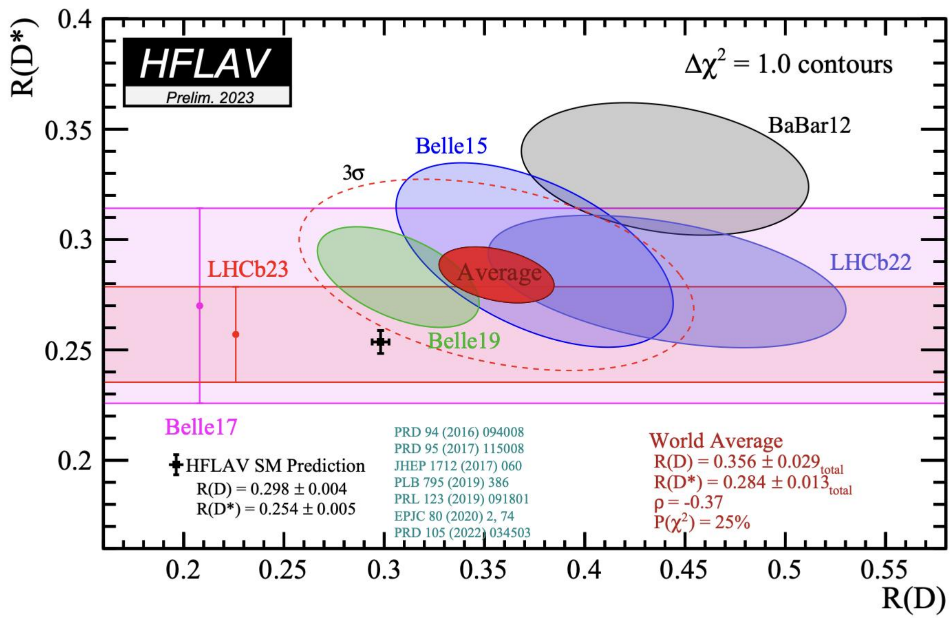
LHCb last year Christmas gift, e-Print: 2212.09153 [hep-ex] Now 1σ

	R_K low-q^2	R_K central-q^2	R_{K^*} low-q^2	R_{K^*} central-q^2
SM prediction	0.9936	1.0007	0.9832	0.9964
SM uncertainty	0.0003	0.0003	0.0014	0.0006

The $R_{D(*)}$ anomalies lowered to 3σ

$$R(D^{(*)}) = \frac{Br(D^{(*)} \to \tau\bar{\nu}_\tau)}{Br(D^{(*)} \to l\bar{\nu})}$$





A lot of BSM studies, Higgs. Z’ , leptoquark...

Muon g-2

Muon a_μ has also been measured to high precision.

BNL experiment (1997 – 2001) final result
for $\Delta a_\mu = a_\mu(\text{exp}) - a_\mu(\text{SM})$ at 2.7σ larger than zero.

FNL experiment first result announce in April, 2021, confirm BNL result but with a high confidence level at 3.3σ.

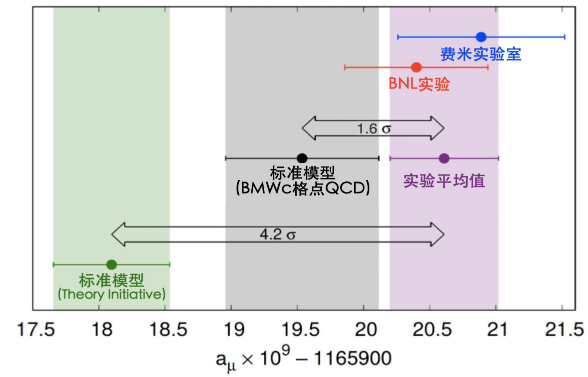
Combining BNL and FNL results, $\Delta a_\mu = 251(59)\times 10^{-11}$.
The deviation away from SM was at 4.2σ level!   IN2021!

Recent Lattice calculation indicate the deviation is only at one σ level.

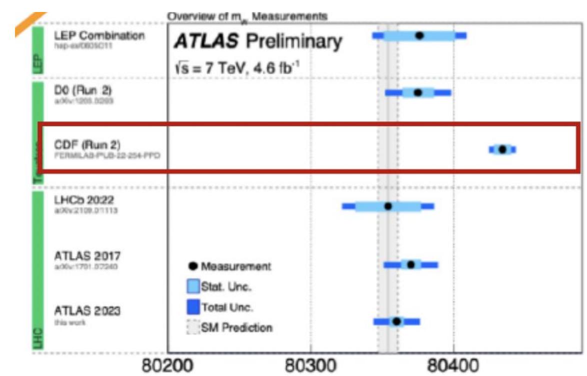
Fermilab final data: $a_\mu = 1165920705(148)\times 10^{-12}$

$$\Delta a_\mu(\text{new}) = a_\mu^{\text{exp}}(\text{new}) - a_\mu^{\text{SM}}(\text{new}) = (39 \pm 64)\times 10^{-11}$$

A lot of efforts have been made to explain this anomaly
Z', leptoquark, higgs….



W mass anomaly



$m_W = 80360 \pm 5_{(\text{stat.})} \pm 15_{(\text{syst.})} = 80360 \pm 16$ MeV

CP violation anomaly in $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$

SM prediction is as follow due to neutrak Kaon mixing

$$A_Q = \frac{B(\tau^+ \rightarrow K_S^0 \pi^+ \bar{\nu}_\tau) - B(\tau^- \rightarrow K_S^0 \pi^- \nu_\tau)}{B(\tau^+ \rightarrow K_S^0 \pi^+ \bar{\nu}_\tau) + B(\tau^- \rightarrow K_S^0 \pi^- \nu_\tau)} = (+0.36 \pm 0.01)\%$$

Experimental measurement differnt by a sign!

$$A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$$

Difficult to produce such a large CP violation even with new physics BSM

Need careful experimental checking!

Flavor violation in leptonic processes

M. Blennow et al., arXiv:2306.010040

Observable	Experimental bound
$\mu \to e\gamma$	$4.2 \cdot 10^{-13}$ [98]
$\tau \to e\gamma$	$3.3 \cdot 10^{-8}$ [99]
$\tau \to \mu\gamma$	$4.2 \cdot 10^{-8}$ [100]
$\mu \to eee$	$1.0 \cdot 10^{-12}$ [101]
$\tau \to eee$	$2.7 \cdot 10^{-8}$ [102]
$\tau \to \mu\mu\mu$	$2.1 \cdot 10^{-8}$ [102]
$\mu \to e$ (Ti)	$4.3 \cdot 10^{-12}$ [103]
$\mu \to e$ (Au)	$7.0 \cdot 10^{-13}$ [104]

3N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$[0.31, 1.0] \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$[0.3, 3.9] \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$1.7 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$[0.35, 1.3] \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$[0.33, 1.0] \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e \theta_\mu^*\rvert}{2}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e \theta_\tau^*\rvert}{2}$	$[1.3, 5.1] \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu \theta_\tau^*\rvert}{2}$	$5.0 \cdot 10^{-6}$	$5.7 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$

$$\theta_\alpha = \frac{\theta}{\sqrt{2}} \left(\sqrt{1+\rho}\, U_{\alpha 3}^* + \sqrt{1-\rho}\, U_{\alpha 2}^* \right) \quad \text{for Normal Ordering (NO),}$$

$$\theta_\alpha = \frac{\theta}{\sqrt{2}} \left(\sqrt{1+\rho}\, U_{\alpha 2}^* + \sqrt{1-\rho}\, U_{\alpha 1}^* \right) \quad \text{for Inverted Ordering (IO),}$$

$$\rho = \frac{\sqrt{\Delta m_{31}^2} - \sqrt{\Delta m_{21}^2}}{\sqrt{\Delta m_{31}^2} + \sqrt{\Delta m_{21}^2}} \quad \text{for NO,}$$

$$\rho = \frac{\sqrt{\Delta m_{23}^2} - \sqrt{\Delta m_{23}^2 - \Delta m_{21}^2}}{\sqrt{\Delta m_{23}^2} + \sqrt{\Delta m_{23}^2 - \Delta m_{21}^2}} \quad \text{for IO,}$$

No flavor violation observed invovle charged leptons, nor CP violation.

What Anomalies tell us?

anomaly – Cambridge Dictionary

noun [C or U] · **UK** /əˈnɒm.ə.li/ **US** /əˈnɑː.mə.li/ FORMAL

a person or thing that is different from what is usual, or not in agreement with something else and therefore not satisfactory:

Statistical anomalies can make it difficult to compare economic data from one year to the next.

The anomaly of the social security system is that you sometimes have more money without a job.

Unitarity, B decays and muon g-2 that are different from SM predictions and therefore not satisfactory.

These anomalies might be some hints of something more that just SM.

Will these anomalies stand with time??? Some of them already went away!
More Data!!!

The need of new physics beyond SM

How good SM is? Is there indications that is may not be the complete theory addressing all problems facing particle physics?

Yes, there are many hints. Some of the prominent phenomenological ones are:

The neutrino mass problem. $P(\nu_1 \to \nu_2) = |<\nu_1(0)|\nu_2(t)>|^2 = \sin^2(2\theta)\sin^2(\Delta m_{21}^2 L/4E)$, $\Delta m_{21}^2 = m_2^2 - m_1^2$.

To give a mass to a fermion in the SM, one needs to pair up a left and right handed partners, example up, down quarks and charged leptons

$$- \quad \bar{Q}_L Y_u \tilde{H} u_R + \bar{Q}_L Y_d H d_R + \bar{L}_L Y_e H e_R + H.C.$$

In the minimal SM, there is not right handed neutrinos in model available, therefore need to introduce them.

Need to introduces ν_R in the model. Then one has $-\bar{L}_L Y_\nu \tilde{H} \nu_R \to \bar{\nu}_L (Y_\nu v/\sqrt{2}) \nu_R$

Then $m_\nu = Y^\nu v/\text{sqrt}[2]$! Problem: $m_\nu/m_e = Y_\nu/Y_e < 10^{-6}$

Why such a small number?

Seesaw models

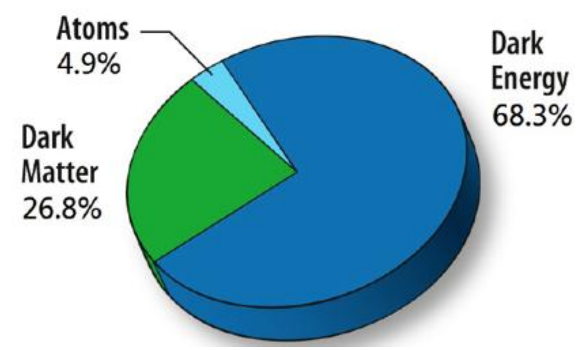
Type I seesaw model: ν_R (1, 1)(0) neutrinos, $-\bar{L}_L Y_\nu \tilde{H} \nu_R - (1/2) m_R \bar{\nu}_R^c \nu_R$, $\quad m_\nu = (Y_\nu v)^2/2m_R$

Type II seesaw model: $\chi(1,3)(-1)$ small vev v_χ, $-L_L Y_\nu \chi L_L^c \to -\nu_L (Y^\nu v_\chi/\sqrt{2}) \nu_L^c$

Type III seesaw model: N_R (1,3)(0),- $\bar{L}_L Y_\nu \tilde{H} N_R - (1/2) m_R \bar{N}_R^c N_R$, $\quad m_\nu = (Y_\nu v)^2/2m_R$

And models of generating neutrino masses at loop levels.

If only confined to leptons, flavor physics and CP violation will be affected in the lepton sector.



Cosmological evidences: Dark matter, Dark energy and Baryon Asymmetry

But what are the specific new physics, not clear!!! A lot to do!

new Higgs, axion, new gauge boson, new fermions, new CPV source, neutral flavor changing current??

Neutrino Physics

New exciting data from Juno, last Nov. the most preciese data for θ_{12}

arXiv: 511.14593 Already 43 citations: $\sin^2\theta_{12} = 0.3092 \pm 0.0087$ and $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \text{eV}^2$

$$V_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \quad V_b = \begin{pmatrix} \frac{2c}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{2s}{\sqrt{6}}, e^{i\alpha} \\ -\frac{c}{\sqrt{6}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{1}{\sqrt{3}} & \frac{c}{\sqrt{2}} - \frac{s}{\sqrt{6}}e^{i\alpha} \\ -\frac{c}{\sqrt{6}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{1}{\sqrt{3}} & -\frac{c}{\sqrt{2}} - \frac{s}{\sqrt{6}}e^{i\alpha} \end{pmatrix}, \quad V_c = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{c}{\sqrt{3}} & \frac{s}{\sqrt{3}}e^{i\alpha} \\ -\frac{1}{\sqrt{6}} & \frac{c}{\sqrt{3}} - \frac{s}{\sqrt{2}}e^{-i\alpha} & \frac{c}{\sqrt{2}} + \frac{s}{\sqrt{3}}e^{i\alpha} \\ -\frac{1}{\sqrt{6}} & \frac{c}{\sqrt{3}} + \frac{s}{\sqrt{2}}e^{-i\alpha} & -\frac{c}{\sqrt{2}} + \frac{s}{\sqrt{3}}e^{i\alpha} \end{pmatrix}$$

Popular model in early 2000, ruled out by Dayabay Data

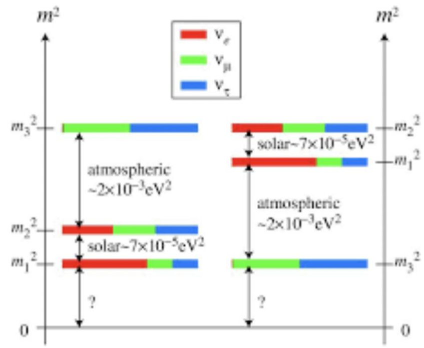
Simple and popular candidate, now 3.6 tension with data

Compatible with data!

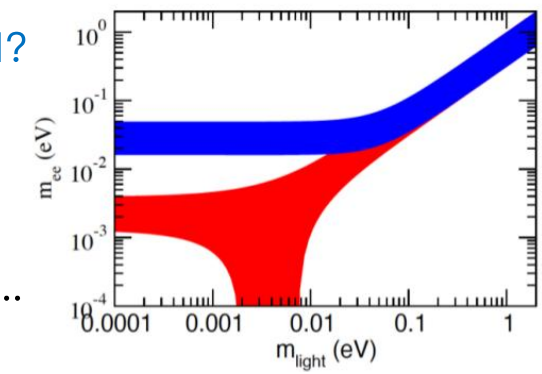
$$\sin^2\theta_{12} = \frac{1 - 3\sin^2\theta_{13}}{3(1-\sin^2\theta_{13})}$$

$$\delta_{CP} = \arg\left(\frac{c^2}{2}e^{-i\alpha} - \frac{s^2}{3}e^{i\alpha}\right).$$

Juno finally mission: neutrino mass hirarchies: NH or IH another ~ 5 years!?



DUNE and hyperK: CP violation. Another N ~ 8 years1?



Compatible with inverted hierarchy. Good by neutrino–less double beta decay measurement!

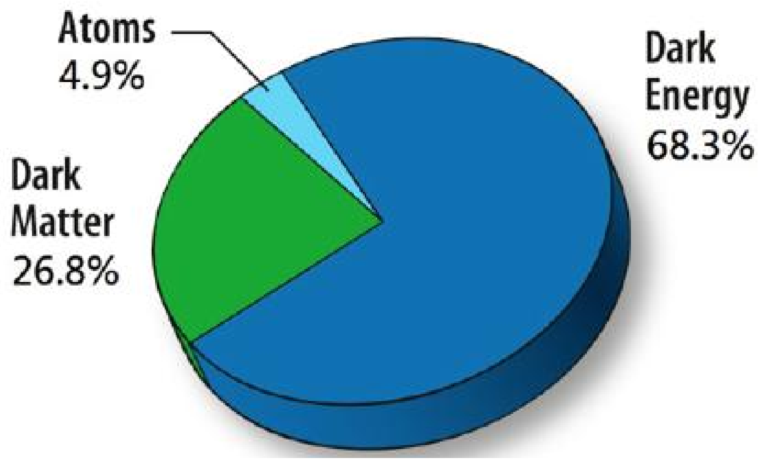
Absolute neutrino mass Katrine and cosmology

Neutrinoless double beta decays: PandaX XT, CDEX....

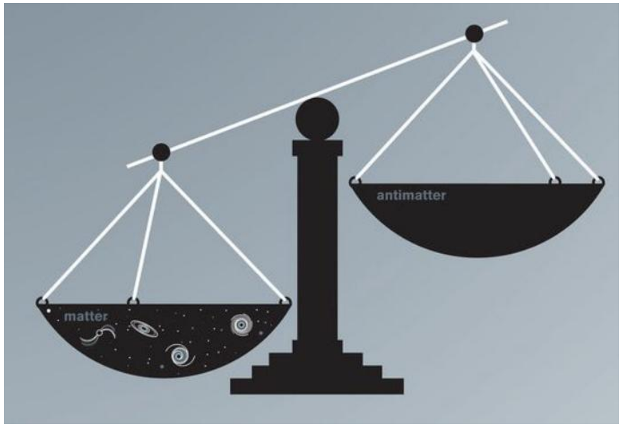
A long time to wait!!

Theory? Later

What are the links for flavor of the Universe



and the origin of the universe?



Why more matter than anti-matter in our Universe?

4. Flavor Physcis and the Origin of the Universe
The thermal history of the Universe

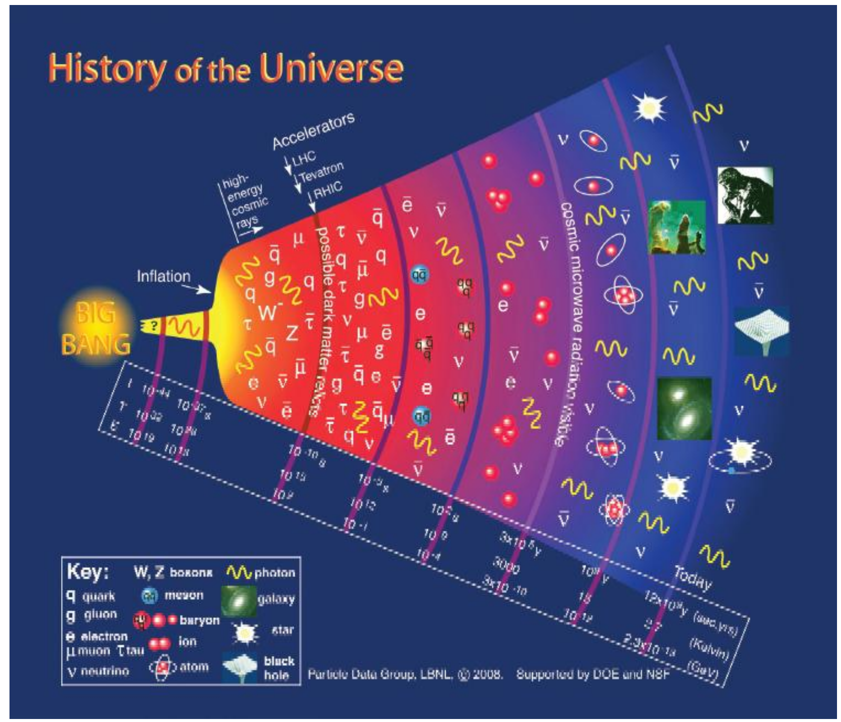
In early universe, all energy forms existed in form of elementary particles, or ….
Temperature is high and were in thermal equilibrium criteria for thermal equilibrium.

???Planck mass T ~ 10^{19}GeV -> Inflation

Big Bang ~ T> 10^{16} GeV

(Not in thermal equillibrium by SM for particle physics)

Grand Unification ~ 10^{16} GeV



EW symmetry breaking 300GeV

Color confinement ~300 MeV

BBN ~ 1 MeV,   CMB ~0.3 eV

Large structure formation

…

Today ~2.7K   Our universe is 14 billoian years old (brong big-bang)

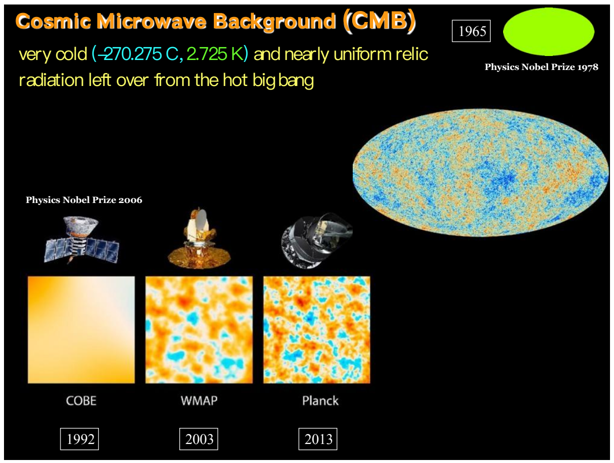
Particle Flavors deeply related to the Origin and the evulation of the Universe

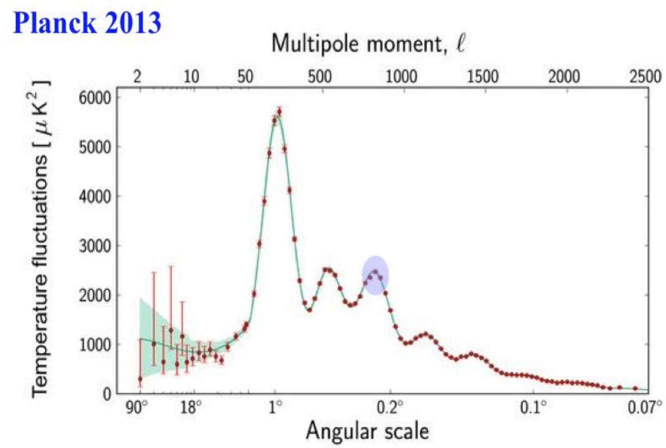
*

CMB, BBN and CvB

Cosmology becomes a precision science, started from CMB.

At z = 1100, the universe became transparent to photons, isotropically come to us, now temparature about 2.7 K.





Universe is a homogeneous and Isotropic one

Location of the first pick determines $\Omega^0 = 1$,

5% energy budge from ordinary matter, many more ...

What consists the other 95% energy budget of our universe?

Earliest direct observational flavor effects for our Universe

BBN (big bang nucleosynthesis)

Light elements start to form at T ~ 1 MeV

Abundance of each element depends on baryon/photon ratio. Consistent value emerges Ω^0_M ~5%

Also powerful probe of new physics:

N_{eff}=3 light neutrino

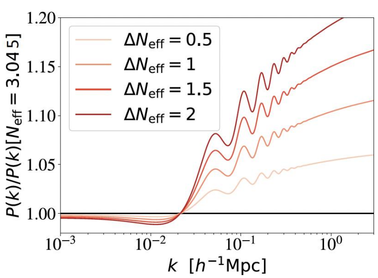
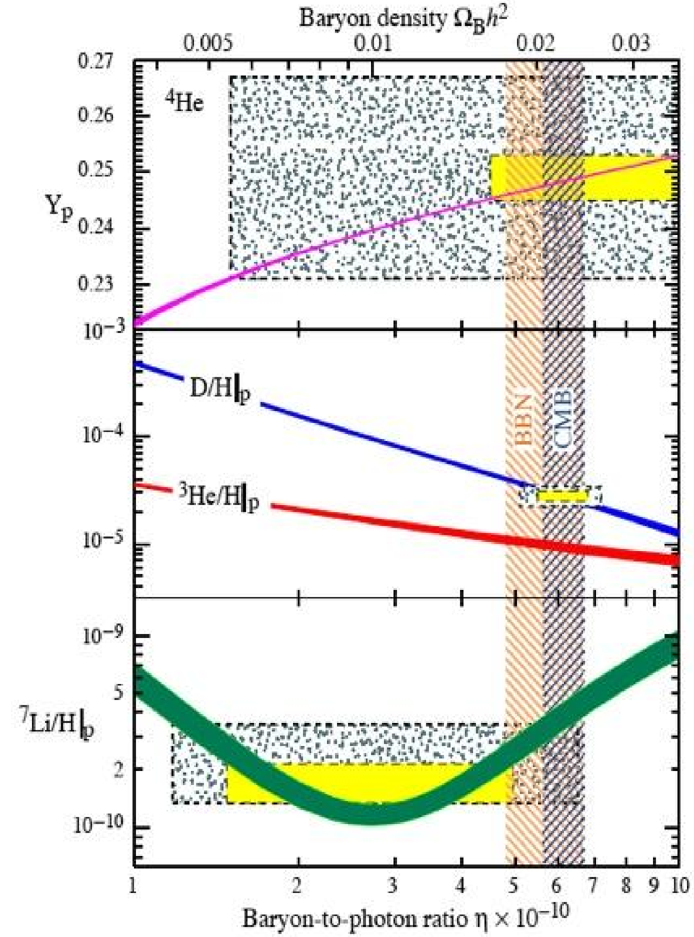


Table 26.1: Summary of $N_{\rm eff}$ constraints.

	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$	[22]
" + BAO + R21	ΛCDM+$N_{\rm eff}$	3.34 ± 0.14 (68%CL)	[11]
"	" +5-params.	2.85 ± 0.23 (68%CL)	[23]



Any light new particles, axion, dark photon...will affect the expansion rate, and therefore the flavor of our Universe is constrained!

Cosmic neutrino background, yet to be directly observed!

Relic neutrino density:

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11}\right)^{4/3}$$

Neutrino back ground temperature: $T_\nu/T_\gamma = (4/11)^{1/3} = 1.95$ K

$n_\gamma = 440/\text{cm}^3$, $n_\nu = 339/\text{cm}^3$

Energy density from neutrinos:

$$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\text{crit}}^0} = \frac{\sum m_\nu}{93.14 h^2 \text{ eV}}$$

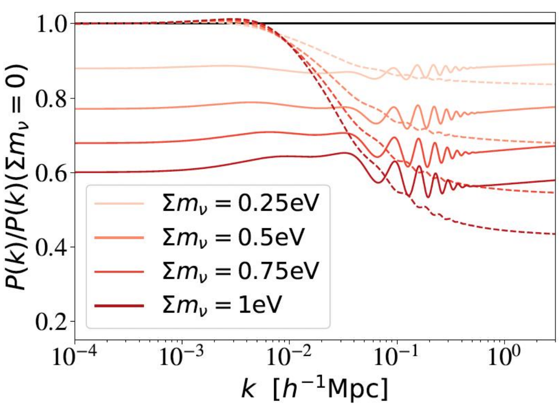


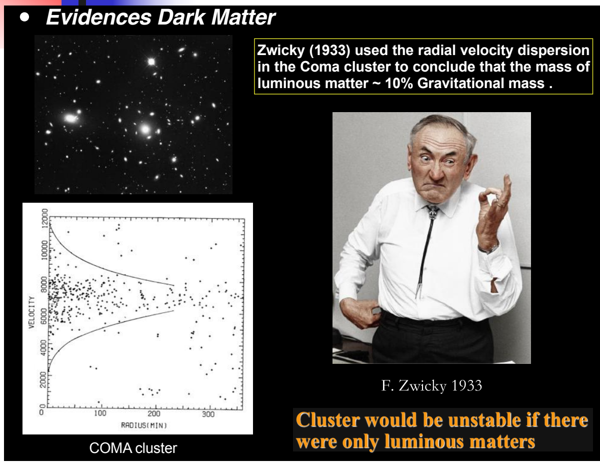
Table 26.2: Summary of $\sum m_\nu$ constraints.

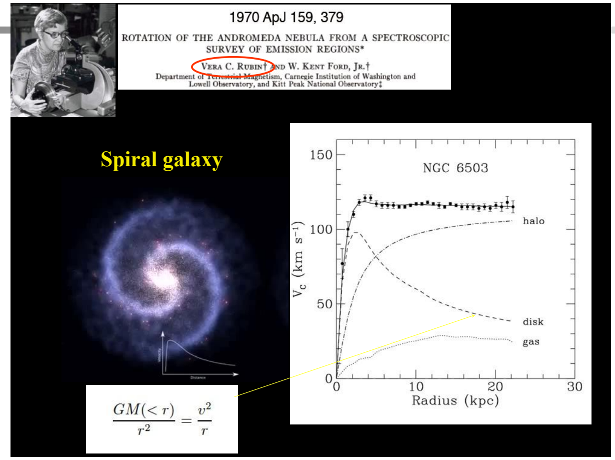
	Model	95% CL (eV)
CMB alone		
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515
CMB + LSS		
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24
CMB + probes of background evolution + LSS		
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13

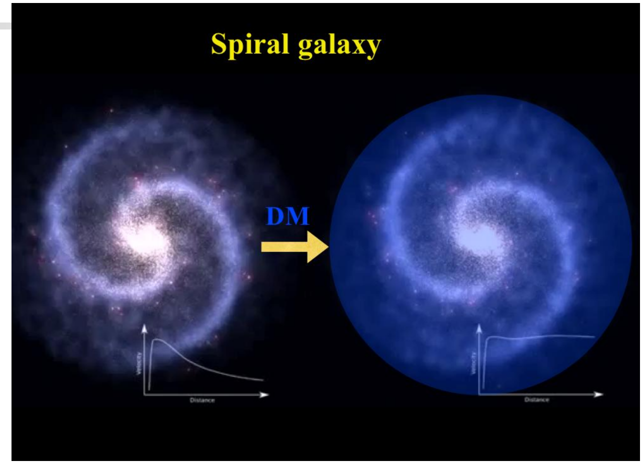
Combined with oscillation data, individual neutrino mass can be determined!

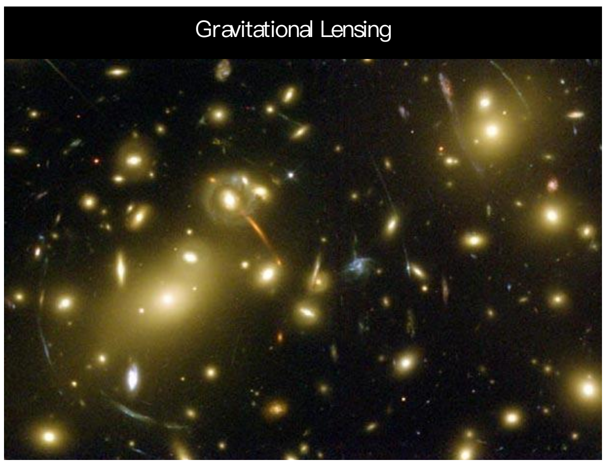
Conflict?

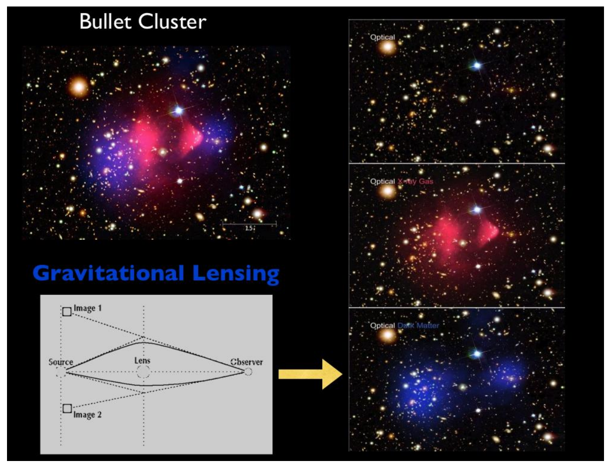
The need of dark matter

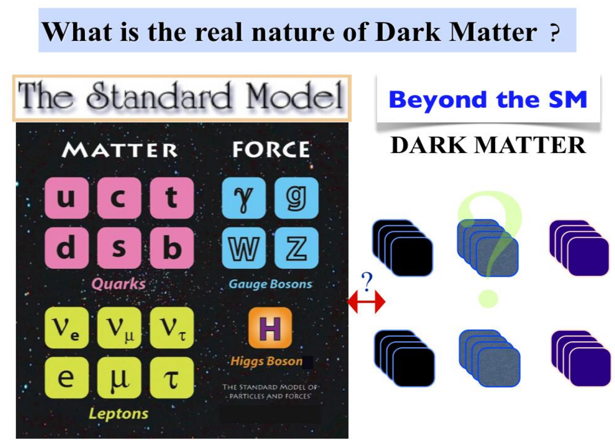






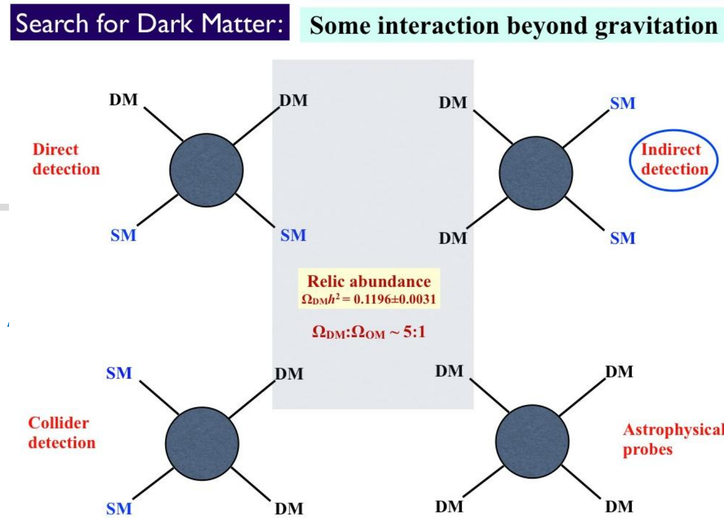






Also from large structure formation! Need dark matter to have the correct cluster structure! Only 27% of the energy budget of the Universe is enough!
Enlarge the flavor content of our universe? But what is it???

Dark matter candidate particles



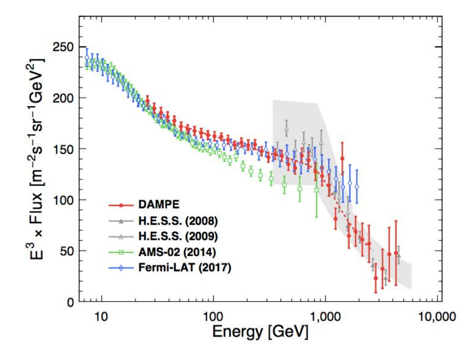
Weakly interacting massive particle (WIMP)

for example: Scalar, fermion, vector, SUSY particles,

ave like: fuzz dark matter, light axion...

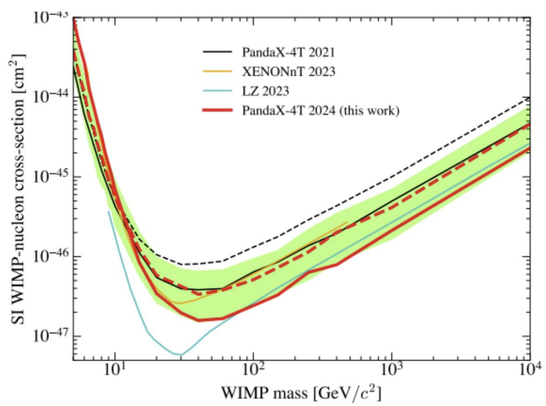
No clue! Many ways to detect it, collisions, cavities,

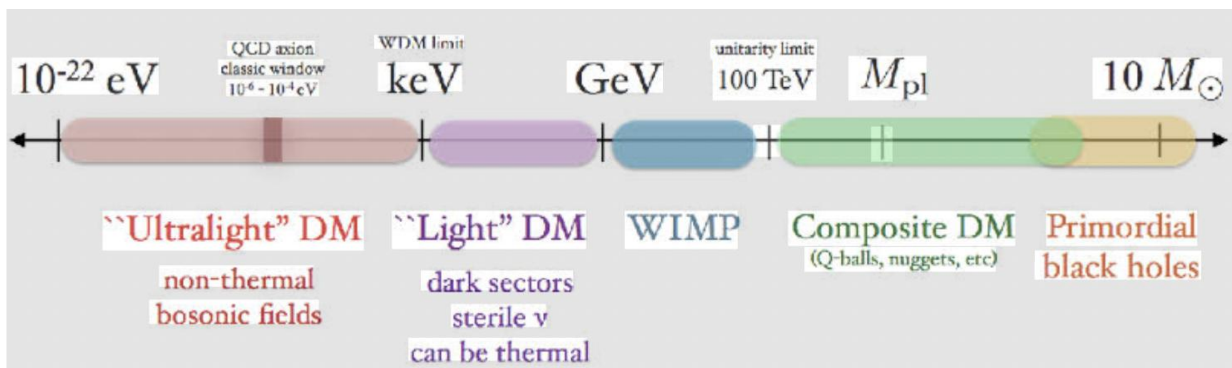
Migdal effects? Key to detect something! Not just limits!!



Dark matter portal mechanisms:

Higgs portal, Nuetrino portal, dark photon portal…





Rare flavor decays and dark matter

He, Ma, Schmidt, Valencia, Volkas, JHEP 07 (2024)168; He, Ma, Tandean, Valencia, PRD112(2025)055025

Recent BELLE-II and NA62 results

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\texttt{exp}} = (2.3 \pm 0.7) \times 10^{-5}$$

$$\mathcal{B}(K^+ \to \pi^+ + \not{E})_{\text{exp}} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

There is an excess for B to K vv

There is the $\Delta\mathcal{B}_K = (4.6^{+3.4}_{-3.2}) \times 10^{-11}$ window for something new !

The SM predictions

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\texttt{SM}} = (4.43 \pm 0.31) \times 10^{-6}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

DM couplings to SM are flavor dependent

There is the window of a light dark matter for invisible decays!!!

A light flavorful dark matter solution -- DM couplings are flavor dependent

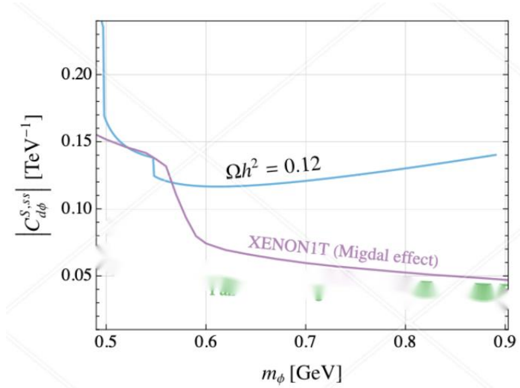
The B^+ -> K^+ invisible is due to B^+ -> K^+ Φ Φ (Φ dark matter). At the quark level due to: b -> s Φ Φ.

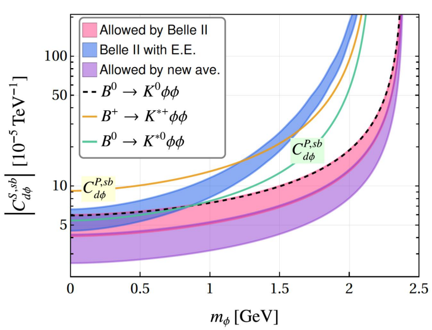
The allowed $\Delta\mathcal{B}_K = (4.6^{+3.4}_{-3.2}) \times 10^{-11}$ for K^+ to π^+ Φ Φ is due to, at the quark level: s -> d Φ Φ

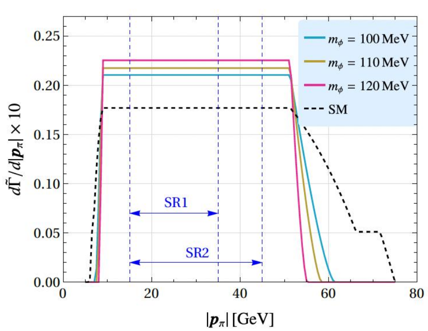
$(m_{K^+} - m_{\pi^+})/2 = 177\,\text{MeV}$ in order that the K^+ channel with the DM could occur.

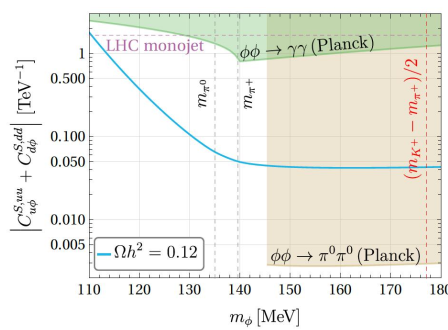
If true, one should also check if the right relic density for DM can be realized.

At the quark level due to: Φ Φ -> dd, uu!









It worked well!
But aken Migdal effect tinto account, problem!

The Migdal effects

Direct observation of the Migdal effect induced by neutron bombardment

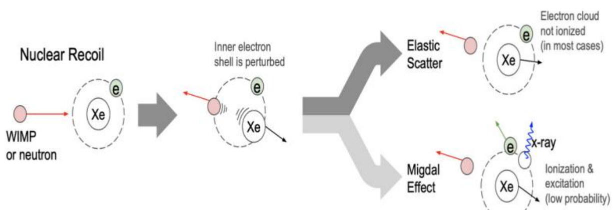
Difan Yi, Qian Liu, Shi Chen, Chunlai Dong, Huanbo Feng, Chaosong Gao, Wenqian Huang, Xinmei Jing, Lingquan Kong, Jin Li, Peirong Li, Enwei Liang, Ruiting Ma, Chenguang Su, Liangliang Su, Junwei Sun, Dong Wang, Junrun Wang, Zheng Wei, Zeen Yao, Yunlinchen Yu, Yu Zhang, Shiqiang Zhou, Zhuo Zhou, ... Yangheng Zheng + Show authors

Nature **649**, 580–583 (2026) | Cite this article

The Migdal effects and light DM constraints

Threshold of electron too recoil for Xenon experiment: ~ 100 eV

The Migdal effects has been recently observed in ordinary nuclear interactions!



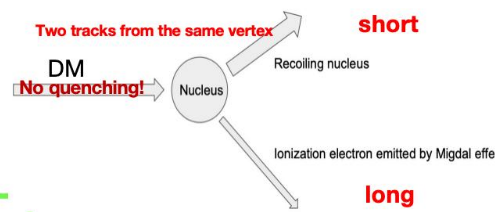
$$B_q^N \equiv \frac{\langle N(\boldsymbol{k},r)|\bar{q}q|N(\boldsymbol{k},r)\rangle}{2m_N} = \frac{m_N}{m_q} f_{Tq}^{(N)}$$

$$f_{Tu}^{(p)} = 0.018(5)\,,\quad f_{Td}^{(p)} = 0.027(7)\,,\quad f_{Ts}^{(p)} = 0.037(17)$$

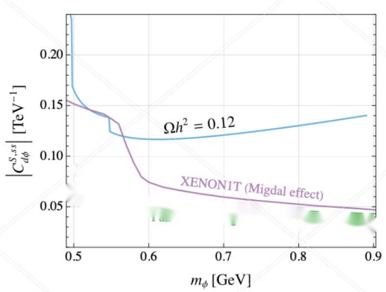
$$f_{Tu}^{(n)} = 0.013(3)\,,\quad f_{Td}^{(n)} = 0.040(10)\,,\quad f_{Ts}^{(n)} = 0.037(17)$$

Light DM recoil energy on nuclei too small, not sensitive.

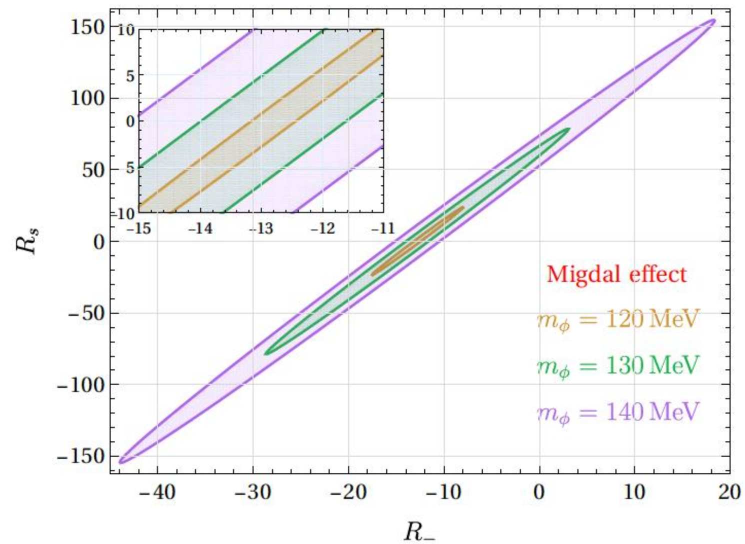
But sensitive to electron reciol energy from Migdal effect



$$\frac{d\langle\sigma_{n,l} v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_n}{8\mu_n^2}[f_p Z + f_n(A-Z)]^2 \int dq\,[q|F_N(q)|^2 \times |F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e,q_e)|^2 \eta(v_{\rm min}(q,\Delta E_{n,l}))]$$



$$R_- = \frac{C_{u\phi}^{S,uu} - C_{d\phi}^{S,dd}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}\,,\qquad R_s = \frac{C_{d\phi}^{S,ss}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}\,.$$



Further test of such models: Using another Nuclear target, such as CDEX data (^{68}Ge...) carry out a similar ananlysis!!

If there is only one type of flavor interaction, Migdal effect rule out the model!

But there are different quarks inside the nuclei, can cellation may happe, the model can work!

Dark Energy

Accelerating expansion of the Universe

- ***The Accelerating Universe: Dark Energy***

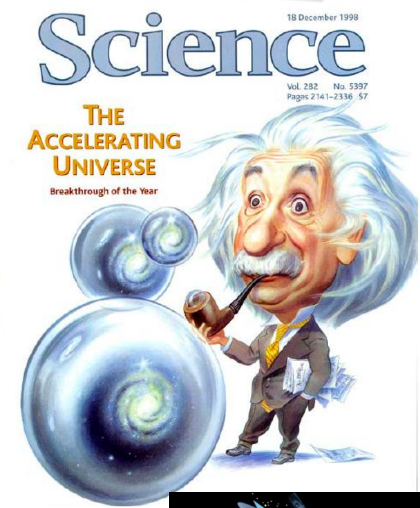
Big News in 1998!

High-Z Team

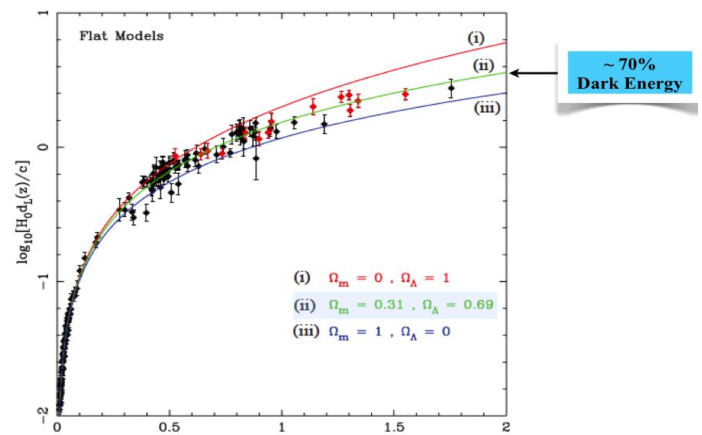
Riess et al. (1998)

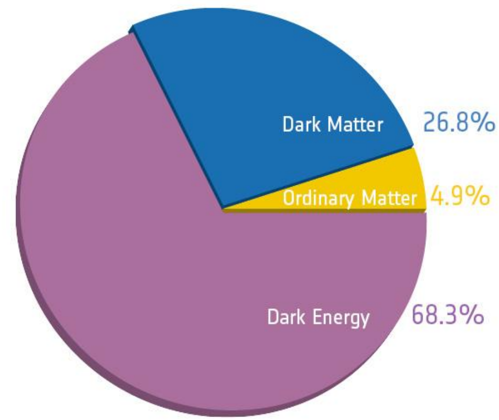
Supernova Cosmology Project

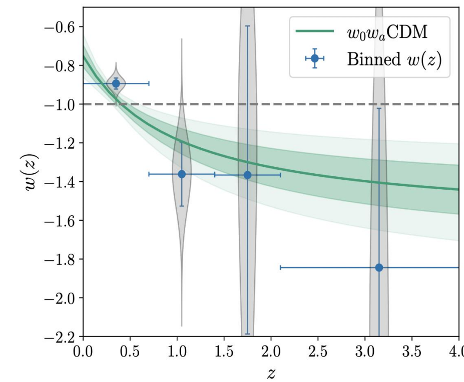
Perlmutter et al. (1999)



More data over the past 10 years







Cosmological constant or more dynamic changing equation of state parameter model?

Recent data seem to indicate the later!!

*

What is a dark energy?

A type of energy which causes our universe to expands with acceleration!

Crucially depends on equation oif state parameter ω= P/ρ

To have the decceleration parameter q_0 to be larger than zero,

$\omega_i < -1/3$ is needed.

Vacuum energy has $\omega_\Lambda = -1$

and can be a candidate for dark energy.

Fits data well!

The standard model of cosmology: Big Bang + Cosmological constant.

Dark energy candidates: Cosmological constant, (chanllenge from DESI data!) Quintessences, ….. Or modify Einstein equation!

Will our local galaxy torn up by cosmological constant?

PHYSICAL REVIEW D, VOLUME 65, 123518

Future island universes in a background universe accelerated by a cosmological constant and by quintessence

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(Received 26 December 2001; published 18 June 2002)

We study bound object formation in a background universe accelerated by a cosmological constant and by quintessence. If the acceleration lasts forever, due to the existence of an event horizon, one would have naively expected the universe to approach a state of cold death. However, we find that many local regions in the universe can in fact be protected by their own gravity to form miniuniverses, provided that their present matter densities exceed some critical value. In the case with a cosmological constant (Λ cold dark matter cosmology), the condition for forming a miniuniverse is that the ratio of the present density parameters $\Omega_i^0/\Omega_\Lambda$ should be larger than a critical value 3.63. Such miniuniverses typically weigh less than 2×10^{14} solar masses, with the lighter ones having tight and compact configurations. In the case with quintessence, the final ratio Ω_i/Ω_q of a miniuniverse is found to be always larger than $w_q^2-w_q$, where w_q is the equation-of-state parameter.

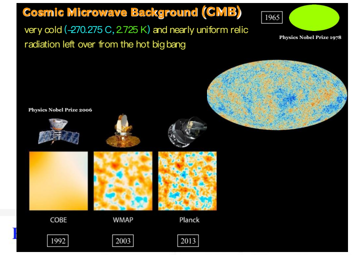
DOI: 10.1103/PhysRevD.65.123518 PACS number(s): 98.80.Es

Please to report: No. We are safe.

Our local galaxy density over comes cosmological constant torn.

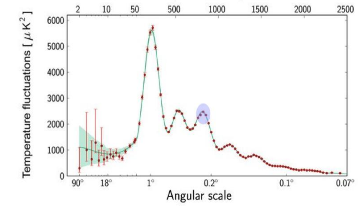
*

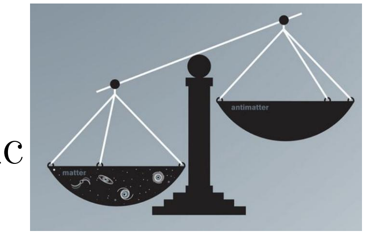
Flavor physics and our matter Universe



In our Universe, matter dominates over anti-matter

- Why this is so is the problem of Baryon Asymmetry of our Universe (BAU)





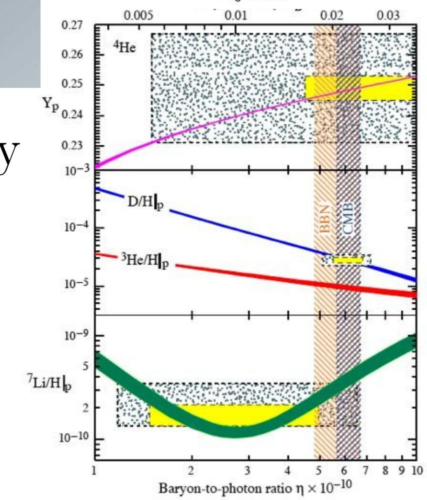
In cosmological terms, the problem is as follows

If initially, the universe is matter and anti-matter symmetric

$n_B/n_\gamma = n_{\bar{B}})/n_\gamma \sim 10^{-20}$

$n_B(n_{\bar{B}})$ - baryon (anti-baryon) number density, n_γ - photon number density

Andrei Sakharov on *Soviet Nobel Peace Prize winners*, the USSR stamp issued on 14 May 1991



However observation, BBN and CMB, show that

$\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 6 \times 10^{-10}$

There is a 10^{10} order of magnitude difference.

Initially, there is a baryon asymmetry?

But inflation will dilute any asymmetry to zero.

Possible to generate a η which fits observtion

from an, initially, matter anti-matter symmetry universe?

Sakharov Conditions (1967)

Baryon Number B Violation

C and CP Violation

Interactions Out Of Thermal Equilibrium

Leptogenesis

Fukugita and Yanagida, PLB174, 45(1986)

Translate lepton number asymmetry generated in the early universe to baryon number asymmetry!

Requires lepton asymmetry generated before Sphelaron effects to be in effective ($T \sim 10^{12}$ – a few TeV).

Initial: $a_L(i)=a$, $a_B(i)=0$.

Sphelaron effect: Conserve B-L, but violates B+L

After: $a_L(f)+a_B(f) = 0$, $a_L(i) - a_B(i) = a_L(f) - a_B(f)$

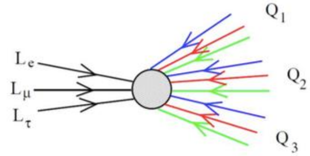
$a_L(f) = a/2$; $a_B(f) = -a/2$

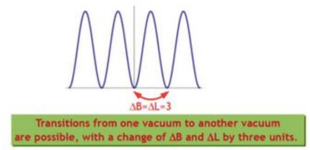
half of initial lepton asymmetry will be translated into baryon asymmetry if complete.

SM Sphelaron effect: $a_B = -(28/79)a_L$ Generating a none-zero a_L ?

Standard Model Has All Ingradients, But Too Small

Baryon number violation: Sphelaron effects-tunneling effects from different vacuum states with non-zero baryon number differences. Violated B+L, but conserves B-L.





C and CP violation: Electroweak interaction violates C, and phase in Kobayashi-Maskawa mixing matrix violates CP.

Out of thermal equilibrium: Electroweak symmetry breaking

But, CP violation rate too small, out of thermal equilibrium too weak. Not enough to generate a large enough Baryon Asymmetry.

If Higgs mass is less than 70 GeV, second order phase transition at electroweak symmetry breaking, too weak.

$\eta \sim 10^{-20}$ Too small. Needs to go beyond SM!

New physics beyond SM needed: well related to flavor physcis

Having larger CP violating effects: from multi-Higgs model, left-right models..... experimentally well connected to EDM searches

Electroweak baryogenesis, Leptogenesis, Gut baryogenesis…. Which one?

Seesaw model plays the right role

$$L_M = -\bar{L}_L Y_e \tilde{H} E_R - \bar{L}_L Y_\nu H \nu_R - \frac{1}{2}(\bar{\nu}_L, \bar{\nu}_R'^c) M^\nu \begin{pmatrix} \nu_L'^c \\ \nu_R' \end{pmatrix} + H.C.$$

The last term violates lepton number L by two units!

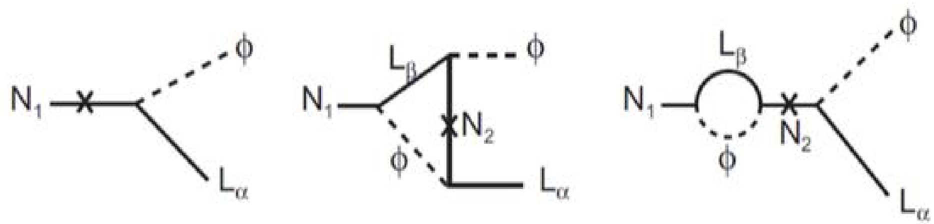
Out of thermal equilibrium decay, new CP violation in N -> L h(ϕ)

N decays into L and anti-L differently

$$a_i = \frac{\Gamma(N_i \to L\phi) - \bar{\Gamma}(N_i \to \bar{L}\phi)}{\Gamma(N_i \to L\phi) + \bar{\Gamma}(N_i \to \bar{L}\phi)}$$

$$a_i \approx -\frac{1}{8\pi}\frac{1}{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ii}} \sum_j Im\{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ij}^2\} f\left(\frac{M_j^2}{M_i^2}\right)$$

$$f(x) = \sqrt{x}\left(\frac{2}{x-1} + \ln\frac{1+x}{x}\right).$$



M_N and m_ν masses are correlated to obtain the right number for η, m_ν of order 0.05 eV, $M_N \sim 1000$ GeV.

Neutrino Seesaw model is a viable model for Baryon Asymmetry of our Universe

Early leptogenesis concentrated on large heavy neutrino mass of order larger than 10^9GeV. Really need that high? How to probe it?

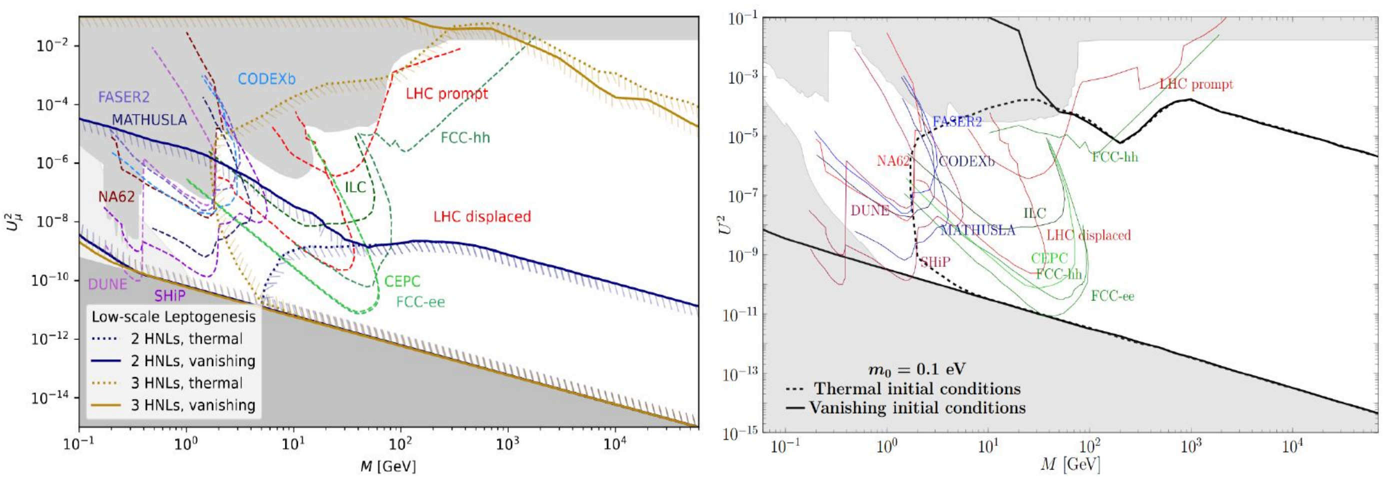
Usually taken to be grand unification scale (SO(10) model requires so) Not possible to probe the heavy degrees of freedom directly.

Lower seesaw scale? $m_\nu \sim m_\tau^2/M$, M~ $6\text{x}10^7$ TeV; $m_\nu \sim m_e^2/M$, M~ 5 TeV

May be testable at colliders for heavy degrees of freedom!

Leptogenesis at TeV scale? Yes. Resonant leptogenesis (Pilaftsis and Underwood (2004)). Degenerate 2 heavy neutrinos are enough for leptogenesis

Frampto, Glashow and Yanagida



Left 2 (3) heavy neutrinos blue (orange) curves (m_0=0), right m_0 = 0.1 eV.

For Type III, there is an associated charged particle, a TeV mass, may be probed at colliders.

Occam Razor: no need the 3rd neutrino for leptogenesis, and make use of it to address some other problem-- plays the role of Dark Matter!

5. Conclusions A lot of opportunities in flavor physics

Flavor physics is a very lively field of research with a lot of new data coming from experiments. Flavor physics is deeply related to the origin of the Universe, and its evolution.

SM is being tested to very good precisions in many ways, but in many cases experimental data precisions are better than theoretical ones, need more support for theoretical calculations and then allow theory to play the role of guiding! g-2 of muon is an interesting example.

New physcis is needed from laboratory and cosmological data. A lot of new ideas have been proposed. Need more data from laboratory and cosmological observations to lead the direction to narrow down possibilities!

Thank you for your attentions