Meeting the challenges of relic neutrinos

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- **BNL-HET**

- **EPS July 29, 2021**
- **[virtual meeting]**
- **Work in progress with Bhupal Dev [Washington Univ, St. Louis, MO]**
- **[Note: most refs missing in talk..]**

Outline

- Introduction and motivation
- Relevant inputs
- SM processes
- Non-Standard Interactions (NSI): Two illustrative examples in light of anomalies
- Detection Feasiblity?
- Summary

Introduction and motivation [Very Brief]

- Clearly detection is extremely important and challenging (see below) and that is what makes it so interesting

- Effective Temp of C ν B (Relic nu) ~$1.7 X 10^{-4}$ ev ; we will assume that is considerably smaller than mass of the neutrino undergoing collision

(see below) if not replace with effective momentum

Neutrino mass

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

$\sin^2(\theta_{23}) = 0.539 \pm 0.022$ $(S = 1.1)$ (Inverted order)

$\sin^2(\theta_{23}) = 0.546 \pm 0.021$ (Normal order)

$\Delta m^2_{32} = (-2.524 \pm 0.034) \times 10^{-3}$ eV^2 (Inverted order)

$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}$ eV^2 (Normal order)

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

δ, *CP* violating phase $= 1.36^{+0.20}_{-0.16}\ \pi$ rad

$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%

$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

Based on Osc Data for numerics we'll use

$$m_\nu = \sqrt{\Delta m_{\rm atm}} \simeq 0.05 \text{ eV}$$

Perhaps optimistic

But in practice 3 masses so expect 3 curves (or peaks/dips if relevant) as (say) functions of incident collision energy

Incident threshold energy

- **The numerical value of the neutrino mass is very important because it enters in determining the needed incident energy:**

- **$s \sim 2\, m_\nu \quad X\ E_{inc} \quad \Rightarrow E_{inc} \quad = [s/GeV^2]X10^{10} \quad GeV$**

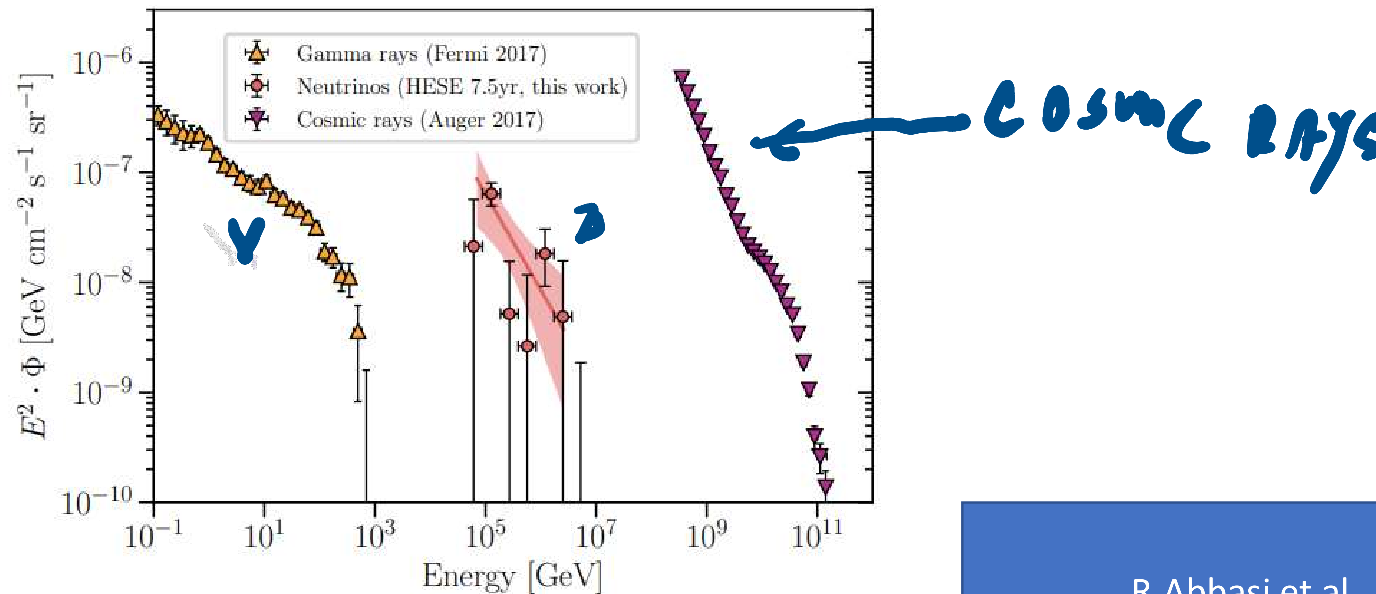


FIG. I.1. ***High-energy fluxes of gamma rays, neutrinos, and cosmic rays.*** The segmented power-law neutrino flux, described in Section VI A 5, obtained in the analysis described in this paper, is shown with red circles. The single power-law assumption, described in Section VI A 1, is shown with the light red region. The high-energy gamma-ray measurements by Fermi [73] are shown in orange, while the extremely-high-energy cosmic-ray measurements by the Pierre Auger Observatory [74] are shown as purple data points. The comparable energy content of these three fluxes is of particular interest in the investigation of cosmic-ray origin.

R.Abbasi et al
[ICECUBE (011.0354)]

$m_\nu \sim .05$ eV

	Particle produced	INC. energy need	comments
	e+ e-	10 TeV	
	mu e	~ 100 PeV	
	mu+ mu-	~ 440 PeV	
	pi+ pi-	~800 PeV	
	rho	~6000 PeV=6 Eev	
	phi	1.05 Eev	
	psi	~ 10EeV	
	Upsilon	~ 100 EeV	
	Z NSI Z'(1.8 GeV) NSI Z' (50 MeV)	8X1000 EeV 32 Eev 55 PeV	

"SKEW"

ICECUBE few PEV

Balloon expt few x100 PEV

OBSERVED DOF

52.3 σ and R in e^+e^- Collisions

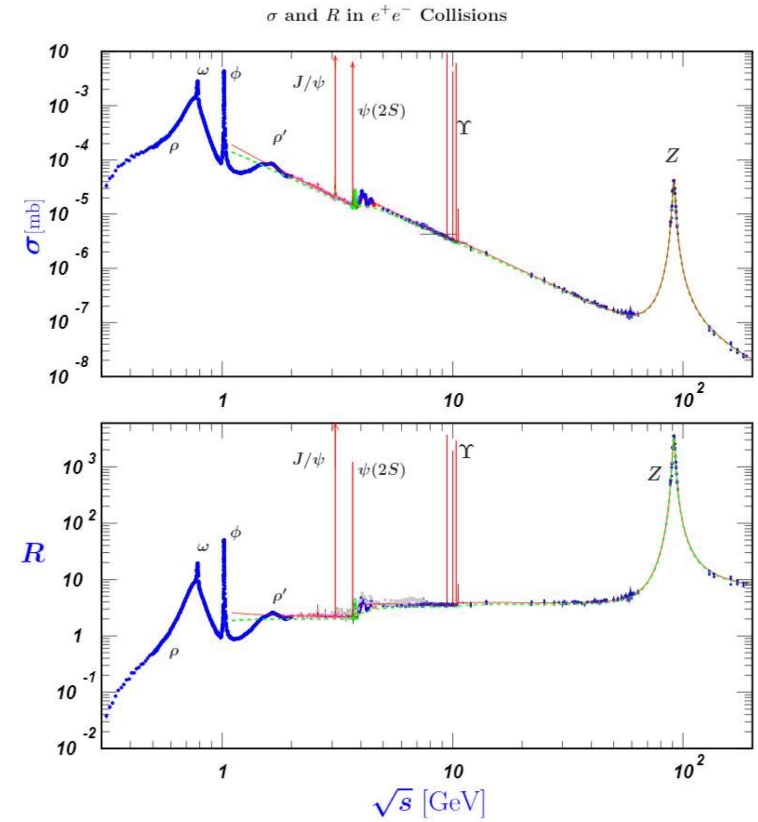
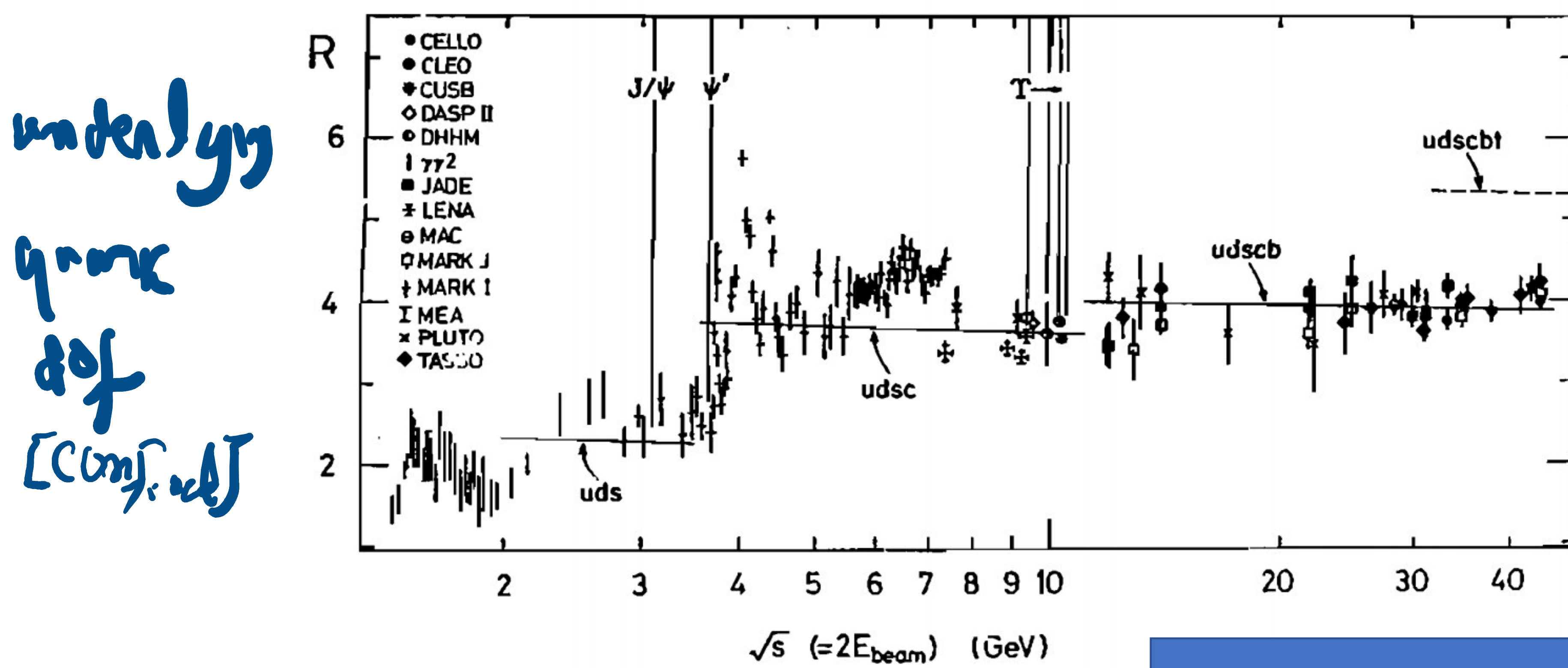


Figure 52.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.7) or, for more details [99], Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1,2,3,4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in [100]. Corresponding computer-readable data files are available at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2019. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))

Figs from PDG
Dim reasons require QED
XS fall as 1/s



BARGER & PHILLIPS

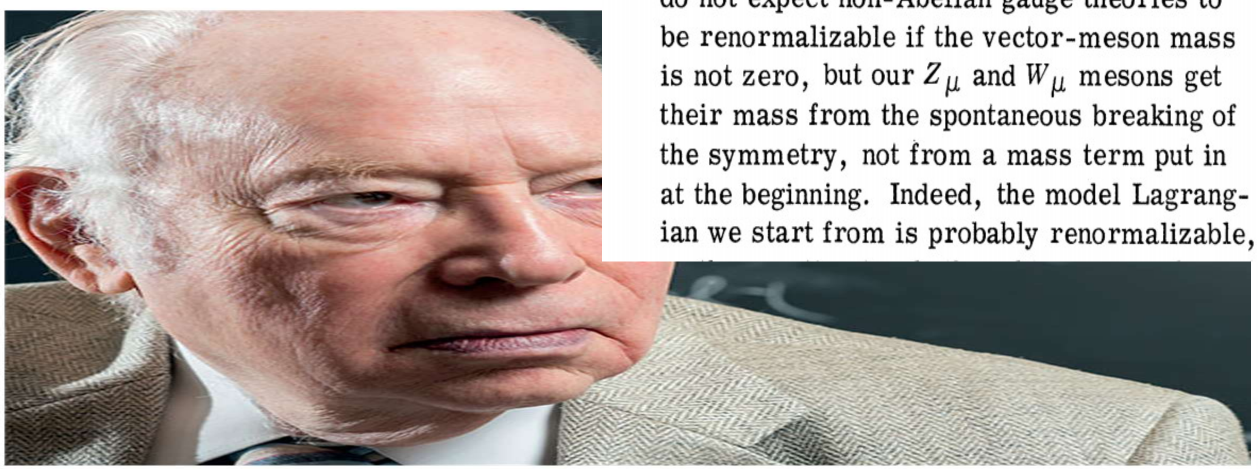
Fig. 4.10. Ratio R of cross sections $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$.

GIANT SUPERMAN OF PHYSICS!

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious dif-



groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable,

IN MEMORIAM

$$\varphi = \binom{\varphi^0}{\varphi^-} \qquad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$\nu\bar{\nu}$ Collisions

GSW SM ⇓ PDG

$$-e\sum_i Q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu$$ ← Photon QED

$$-\frac{g}{2\cos\theta_W}\sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5)\psi_i Z_\mu \,. \qquad (10.2$$ ← Z weak

The third term in $\mathscr{L}_F$ describes electromagnetic interactions (QED) [8–10], and the last is the weak neutral-current interac- tion [5–7]. The vector and axial-vector couplings are

$$g_V^i \equiv t_{3L}(i) - 2Q_i \sin^2\theta_W \,, \qquad (10.5$$

$$g_A^i \equiv t_{3L}(i) \,, \qquad (10.$$

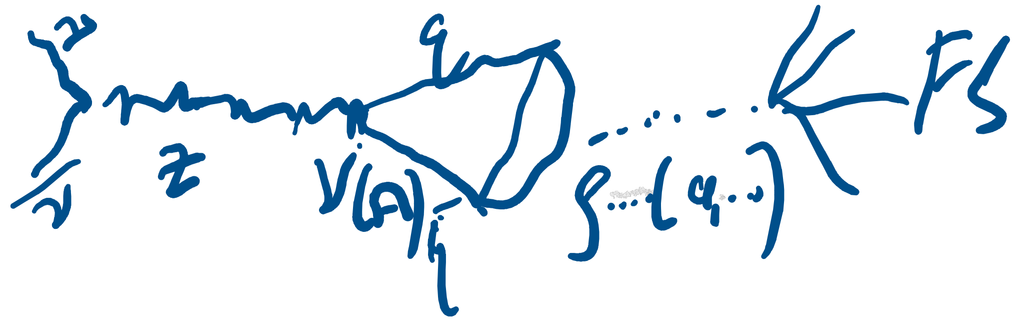
where $t_{3L}(i)$ is the weak isospin of fermion i ($+1/2$ for u_i and ν $-1/2$ for d_i and e_i) and Q_i is the charge of ψ_i in units of e.

PRE-DATES QCD

Hadronic vector current dominated by 1– vectors
[rho, omega, phi, psi, upsilon…..]
See Gounaris & Sakurai; TD Lee & Bruno Zumino,
“field-current identities”
Nothing sacred about 1—
Hadronic weak axial current is dominated by 1++
Resonances,

→ SPECULATION

Eqns above from PDG



Resonance formula:

$$\sigma(\nu_i\bar{\nu}_i \to X^* \to \text{anything}) = \frac{8\pi}{m_X^2}\text{BR}(X \to \nu_i\bar{\nu}_i)\text{BR}(X \to \text{anything})\frac{s\Gamma_X^2}{(s-m_X^2)^2 + \frac{s^2\Gamma_X^2}{m_X^2}}. \quad (1)$$

- BD+AS [WIP]

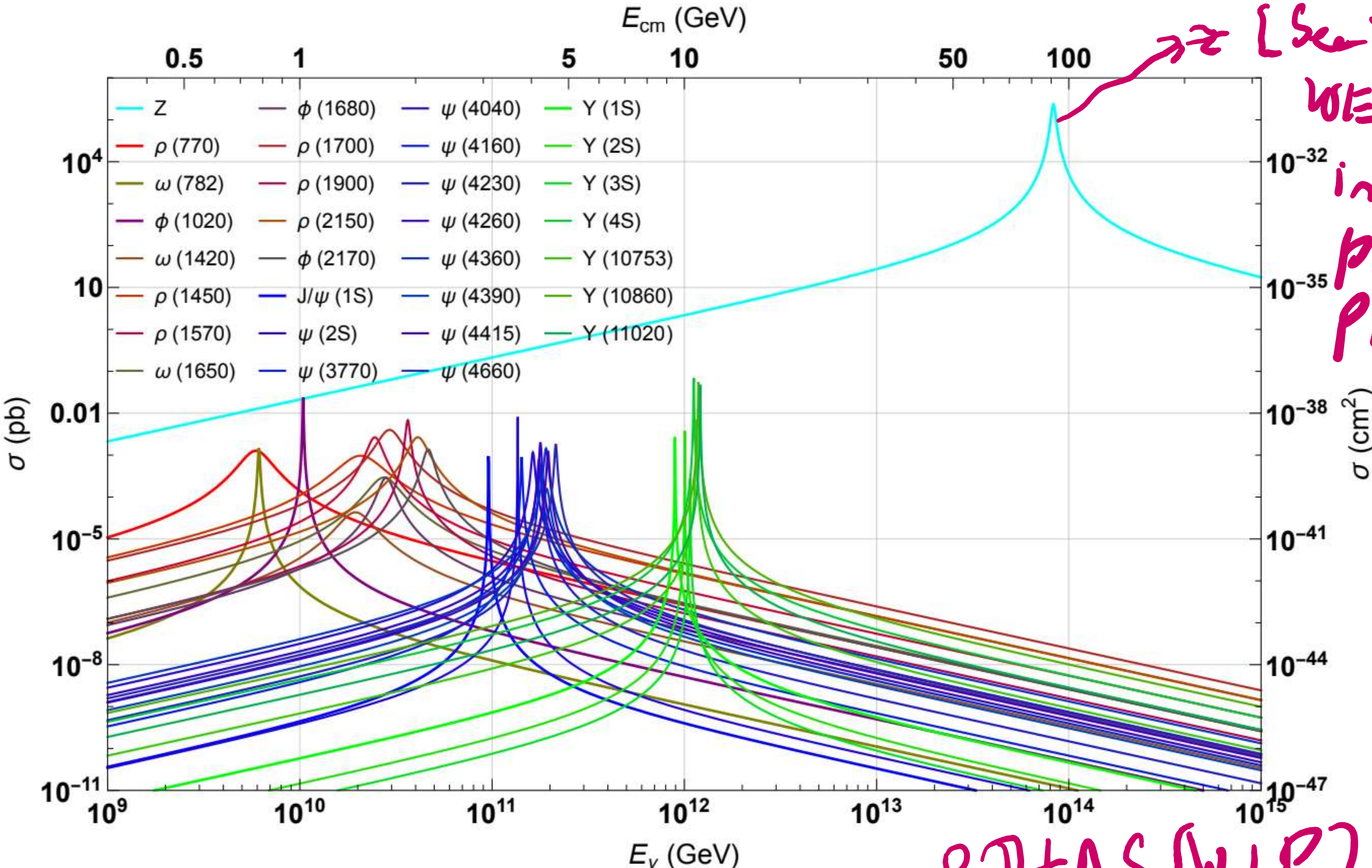
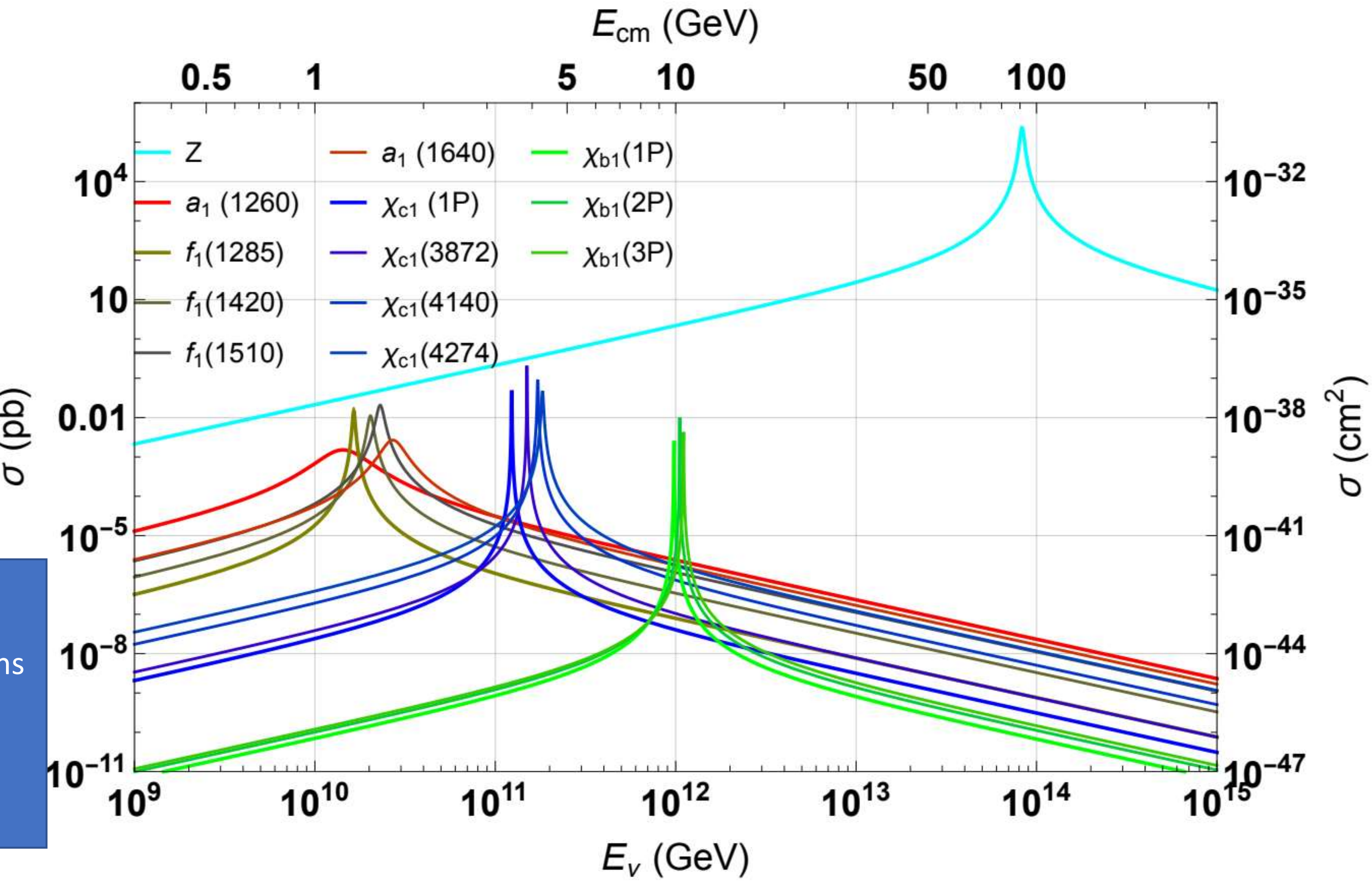


FIG. 1. Vector meson resonances. Z resonance is also shown for comparison. For the lower x-axis, we have assumed $m_\nu = 0.05$ eV to translate $E_{\rm cm}$ into E_ν.

→ Z [See Tom WEILER's inspirational paper PRL '82 + ...]

B.D + A.S (WIP)



For axial mesons appreciable uncertainties

FIG. 2. Axial-vector meson resonances. Z resonance is also shown for comparison. For the lower x-axis, we have assumed $m_\nu = 0.05$ eV to translate $E_{\rm cm}$ into E_ν.

Event Spectrum: The total number of events is given by

$$N = T \cdot N_A \cdot \Omega \cdot V \cdot \int_{E_{\rm min}}^{E_{\rm max}} dE \Phi(E) \sigma(E),$$

where T is the exposure time (which we take 10 years), $N_A = 6.022 \times 10^{23}$ cm^{-3} is the water-equivalent of Avogadro number, $\Omega = 2\pi$ is the solid angle of coverage (only events above horizon are considered; the UHE neutrinos coming from below will be severely attenuated by Earth), Φ is the cosmogenic neutrino flux for which we use the model given in Ref. [11].

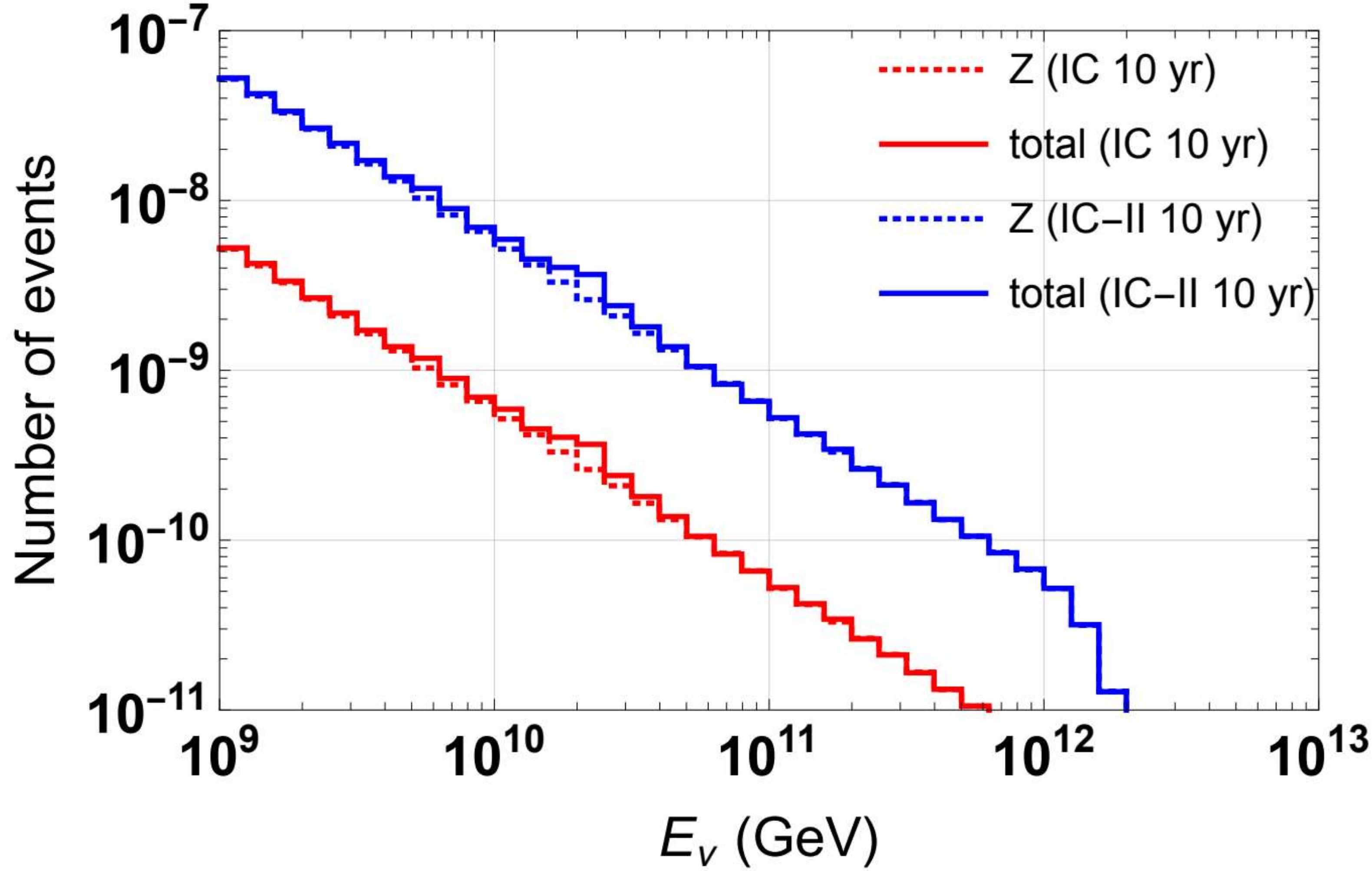


FIG. 3. Event spectrum at IceCube and IceCube-GenII with 10 years of exposure.

Highly abbr. list of refs

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[11] M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen, and S. Sarkar, Astropart. Phys. **34**, 106 (2010), arXiv:1005.2620 [astro-ph.HE].

NSI ex. I: to account for muon (g-2) anomaly

- 0

In the case of a new vector mediator, such a gauge-invariant, renormalisable interaction is given by

$$\mathcal{L} = -g_\mu \, \bar{L}_2 \gamma^\alpha L_2 \, X_\alpha - g_\mu \, \bar{\mu}_R \gamma^\alpha \mu_R \, X_\alpha \,, \tag{4}$$

where $L_2^T = (\nu_{\mu L}, \mu_L)$ and g_μ denotes the coupling of the new vector boson X_α. The Lagrangian in Eq. (4) necessarily implies an equal-strength interaction of the new vector boson with the muon-neutrino as with the muon. In this paper, we want to study the potential of such neutrino interactions

Amarall, Cerdeno, Foldenauer, arXiv:2104.03297

II.2. Benchmark points and analysis strategy

	$M_{A'}$	$g_{\mu\tau}$
BP1	15 MeV	5×10^{-4}
BP2	25 MeV	6×10^{-4}
BP3	50 MeV	6×10^{-4}
BP4	100 MeV	1×10^{-3}

→ for illustration

TABLE I. Benchmark points in the $(g_{\mu\tau}, M_{A'})$ parameter space of a $U(1)_{L_\mu - L_\tau}$ boson favoured by $(g-2)_\mu$. For $U(1)_{L_\mu - L_\tau}$ we use the value of the loop-induced kinetic mixing, $\epsilon_{\mu\tau} = -g_{\mu\tau}/70$.

2. A simplified model

Our simplified model Lagrangian for the Z' coupling exclusively to the muon and tau sector of the SM is given by

$$\mathcal{L}_{Z'} = g'_L(\bar{\mu}\gamma^\alpha P_L \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\tau) Z'_\alpha + g'_R(\bar{\mu}\gamma^\alpha P_R \tau) Z'_\alpha + \text{H.c.}, \quad (2)$$

where $P_{L,R} = (1 \mp \gamma^5)/2$ are the chirality projection operators. Due to $SU(2)_L$ invariance, the couplings of the left-handed neutrinos and charged leptons are identical, whereas we do not introduce right-handed neutrinos in order to keep the model minimal. The left-handed and right-handed couplings g'_L and g'_R could in principle contain CP violating phases. We will take into account the complex nature of these couplings in all the equations below; in our numerical analysis however, we will take them to be real

Altmannshofer, Chen, Dev and AS, PLB 2016

NSI ex. II: to account for muon (g-2) anomaly

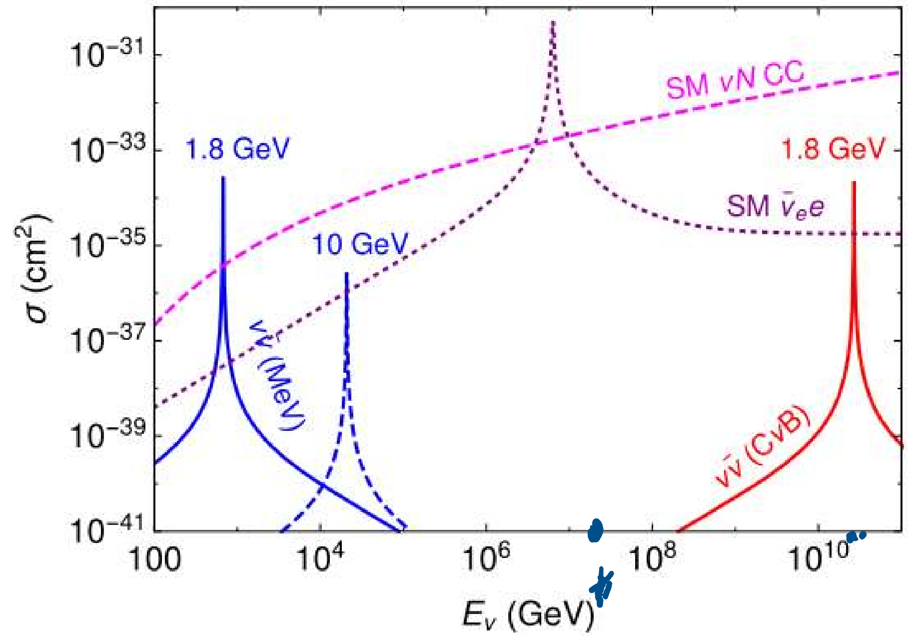

Fig. 9. Cross section for $\nu_i \bar{\nu}_j \to Z' \to f \bar{f}'$ as a function of the energy of one of the initial state neutrinos. For the second neutrino ν_j, we consider two cases: CνB (red solid curve) and supernova neutrinos with MeV energy (blue solid and dashed curves). The numbers above the peaks show the Z' mass. For comparison, we also show the SM neutrino–nucleon CC and $\bar{\nu}_e e$ cross sections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ACDS
PLB2016

Summary p1 of 2

- **Detection of relic nu's obviously extremely important and challenging**
- **Inspired by Gounaris+ Sakurai; Lee+Zumino, suggest weak hadronic vector current likely dominated by low lying 1- - vector resonances [rho,omega, phi, psi, upsilon(4S) etc]**
- **Analogously weak axial current is anticipated to be dominated by 1++ axial vector counterpart resonances..**
- **Since nu mass is so small incident energy in collision needed is very high…**

Summary p.2

- **ICECUBE has so far detected around few PeV; Balloon expts data suggests~ few X 100 PeV; Much larger ICECUBE..GENII ..Similarly there are other efforts such as**
- **KM3NET
NEUTRINO TELESCOPE
IN THE MEDITERRANEAN AND MANY MORE ... FUTURE**
- **Given (bunch of over 3 sigma anomalies): RD(*) ~ 3 sigma; RK(*) over 3 sigma; muon (g-2) ~4.2 sigma and also some (few sigma) in the nu sector, chances of NP are rather high….may well have significant repercussions in nu collisions relevant here**
- **SO FAR WE BARELY MANAGED TO SCRATCH THE SURFACE OF COPLEXITY [CHECKS ARE ALSO NEEDED]; CONTINUE STUDY TO POSSIBLY DEVICE OPTIMAL STRATEGIES**

XTRA'S

For the vector case $\mathrm{BR}(V \to \nu_i \bar{\nu}_i)$, we use the following expressions:

$$\Gamma(\rho \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{24\pi}(1 - 2s_w^2)^2 f_\rho^2 m_\rho^3\,, \tag{2}$$

$$\Gamma(\omega \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{96\pi}\left(-\frac{4}{3}s_w^2\right)^2 f_\omega^2 m_\omega^3\,, \tag{3}$$

$$\Gamma(\phi \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{96\pi}\left(-1 + \frac{4}{3}s_w^2\right)^2 f_\phi^2 m_\phi^3\,, \tag{4}$$

$$\Gamma(\psi \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{96\pi}\left(1 - \frac{8}{3}s_w^2\right)^2 f_\psi^2 m_\psi^3\,, \tag{5}$$

$$\Gamma(\Upsilon \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{96\pi}\left(-1 + \frac{4}{3}s_w^2\right)^2 f_\Upsilon^2 m_\Upsilon^3\,, \tag{6}$$

For the axial-vector case $\mathrm{BR}(A \to \nu_i \bar{\nu}_i)$, we use the following expression:

$$\Gamma(A \to \nu_i \bar{\nu}_i) = \frac{G_F^2}{48\pi} f_A^2 m_A^3\,. \tag{7}$$

For the higher resonances, we have estimated the decay constants using the ratio of their $V \to e^+e^-$ decay rates from the PDG and using the formula

$$\Gamma(V \to e^+e^-) = \frac{4\pi}{3}\frac{\alpha^2}{m_V} f_V^2 c_V\,, \tag{8}$$

where the coefficients c_V are given in Appendix C of Ref. [1]. For instance, the decay constant for ω' (1420) is estimated as

$$\left(\frac{f_{\omega'}}{f_\omega}\right)^2 = \frac{\Gamma(\omega' \to e^+e^-)}{\Gamma(\omega \to e^+e^-)}\frac{m_{\omega'}}{m_\omega} = \frac{\mathrm{BR}(\omega' \to e^+e^-)}{\mathrm{BR}(\omega \to e^+e^-)}\frac{\Gamma_{\omega'}}{\Gamma_\omega}\frac{m_{\omega'}}{m_\omega} = \frac{6.6\times10^{-7}}{7.39\times10^{-5}}\frac{290\ \mathrm{MeV}}{8.68\ \mathrm{MeV}}\frac{1410\ \mathrm{MeV}}{782.66\ \mathrm{MeV}} \tag{9}$$

Caveats:

- For $\omega(1420)$, there is $\sim 50\%$ uncertainty on the width: 290 ± 190 MeV.
- For $\rho(1450)$, the e^+e^- BR is not given directly. We used $\mathrm{BR}(\omega\pi) \times \mathrm{BR}(e^+e^-) = 2.1 \times 10^{-6}$ and $\mathrm{BR}(\omega\pi) \sim 0.21$.
- For $\rho(1570)$, we used $\mathrm{BR}(\phi\pi) \times \Gamma(e^+e^-) = 3.5$ eV and $\mathrm{BR}(\phi\pi) = 0.001$ (10% of its upper limit).
- For $\phi(1680)$, we used $\mathrm{BR}(K\overline{K}^*(892)) \times \mathrm{BR}(e^+e^-) = 1.15 \times 10^{-6}$ as the conservative value for $\mathrm{BR}(e^+e^-)$.

Meson (V)	Mass (m_V) [2]	Width (Γ_V) [2]	Decay Constant (f_V)
ρ (770)	775.26 MeV	147.4 MeV	216 MeV [1]
ω (782)	782.66 MeV	8.68 MeV	197 MeV [1]
ϕ (1020)	1019.461 MeV	4.249 MeV	233 MeV [1]
ω (1420)	1410 MeV	290 MeV	144 MeV [Eq. (9)]
ρ (1450)	1465 MeV	400 MeV	225 MeV
ρ (1570)	1570 MeV	144 MeV	218 MeV
ω (1650)	1670 MeV	315 MeV	361 MeV
ϕ (1680)	1680 MeV	150 MeV	111 MeV
ρ (1700)	1720 MeV	250 MeV	336 MeV
ρ (1900)	1909 MeV	48 MeV	182 MeV
ρ (2150)	2034 MeV	234 MeV	245 MeV
ϕ (2170)	2159 MeV	137 MeV	203 MeV
J/ψ (1S)	3096.9 MeV	92.6 keV	418 MeV [3, 4]
ψ (2S)	3686.1 MeV	294 keV	296 MeV
ψ (3770)	3773.7 MeV	27.2 MeV	100 MeV
ψ (4040)	4039 MeV	80 MeV	188 MeV
ψ (4160)	4191 MeV	70 MeV	144 MeV
ψ (4230)	4220 MeV	50 MeV	104 MeV
ψ (4260)	4223.3 MeV	54.2 MeV	199 MeV
ψ (4360)	4368 MeV	96 MeV	220 MeV
ψ (4390)	4390 MeV	139 MeV	87 MeV
ψ (4415)	4415 MeV	62 MeV	162 MeV
ψ (4660)	4630 MeV	62 MeV	196 MeV
Υ (1S)	9460.3 MeV	54.02 keV	649 MeV [4, 5]
Υ (2S)	10023.26 MeV	31.98 keV	460 MeV
Υ (3S)	10355.2 MeV	20.32 keV	399 MeV
Υ (4S)	10579.4 MeV	20.5 MeV	343 MeV
Υ (10753)	10753 MeV	36 MeV	105 MeV
Υ (10860)	10885.2 MeV	37 MeV	340 MeV
Υ (11020)	11000 MeV	24 MeV	222 MeV

TABLE I. Vector mesons with $J^{\text{CP}} = 1^{--}$.

Meson (A)	Mass (m_A) [2]	Width (Γ_A) [2]	Decay Constant (f_A)
a_1 (1260)	1230 MeV	420 MeV	238 MeV [6]
f_1 (1285)	1281.9 MeV	22.7 MeV	172 MeV [7]
f_1 (1420)	1426.3 MeV	54.5 MeV	219 MeV [7]
f_1 (1510)	1518 MeV	73 MeV	336 MeV
a_1 (1640)	1655 MeV	254 MeV	215 MeV
χ_{c1} (1P)	3510.67 MeV	0.84 MeV	344 MeV [8]
χ_{c1} (3872)	3871.65 MeV	1.19 MeV	430 MeV
χ_{c1} (4140)	4146.8 MeV	22 MeV	$\sim$ 250 MeV
χ_{c1} (4274)	4274 MeV	49 MeV	$\sim$ 250 MeV
χ_{b1} (1P)	9892.78 MeV	107.2 keV [9]	265 MeV [10]
χ_{b1} (2P)	10255.46 MeV	133.4 keV [9]	795 MeV
χ_{b1} (3P)	10513.4 MeV	149 keV [9]	851 MeV

Appreciable uncertainties esp due to decay constants

TABLE II. Axial-vector mesons with $J^{CP} = 1^{++}$. The missing decay constants (without references) have been estimated from the available ones using $f_A^2 \propto m_A \Gamma_A$.