



Institute of Theoretical Physics
Chinese Academy of Sciences

中微子理论进展、超出标准模型的新物理进展综述

Theoretical Overview on Neutrino and New Physics

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Outline

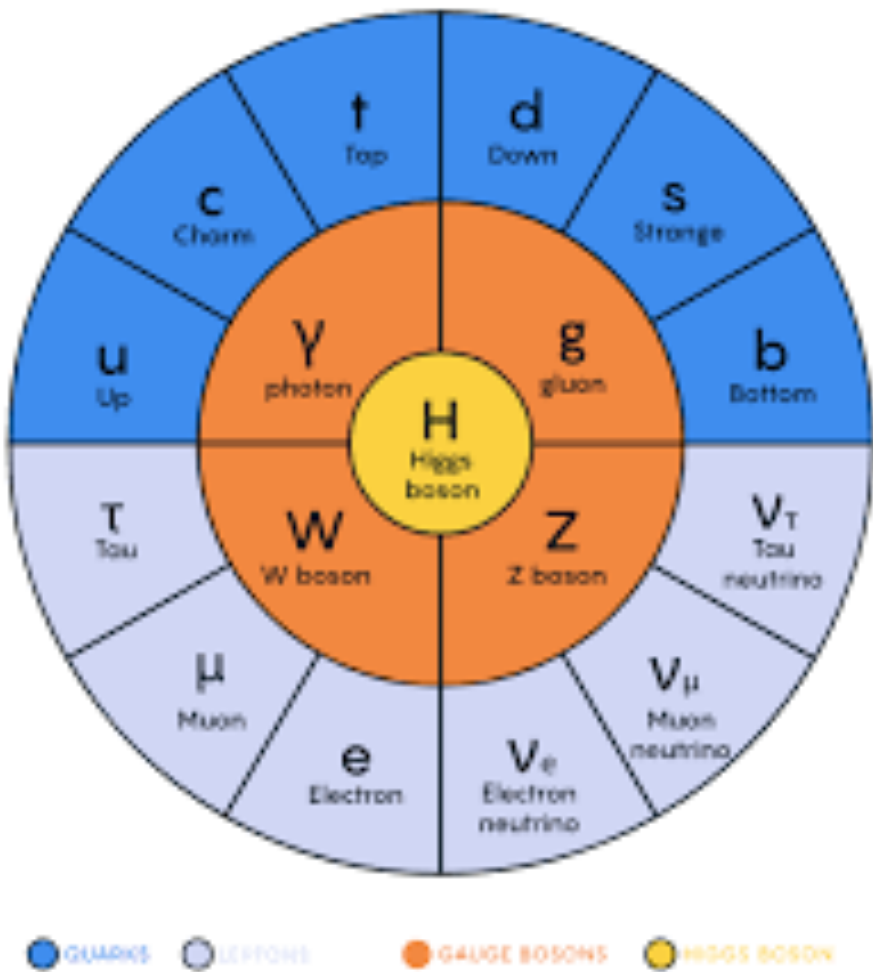
- Motivation for new physics
- New physics model building: Higgs and neutrino
- New physics from EFT: neutrino as example
- New way of searching new physics
- Summary and outlook

Disclaimer: Too broad subject
Apologize if your interesting topic or your related work
is missing ...

Motivation for New Physics

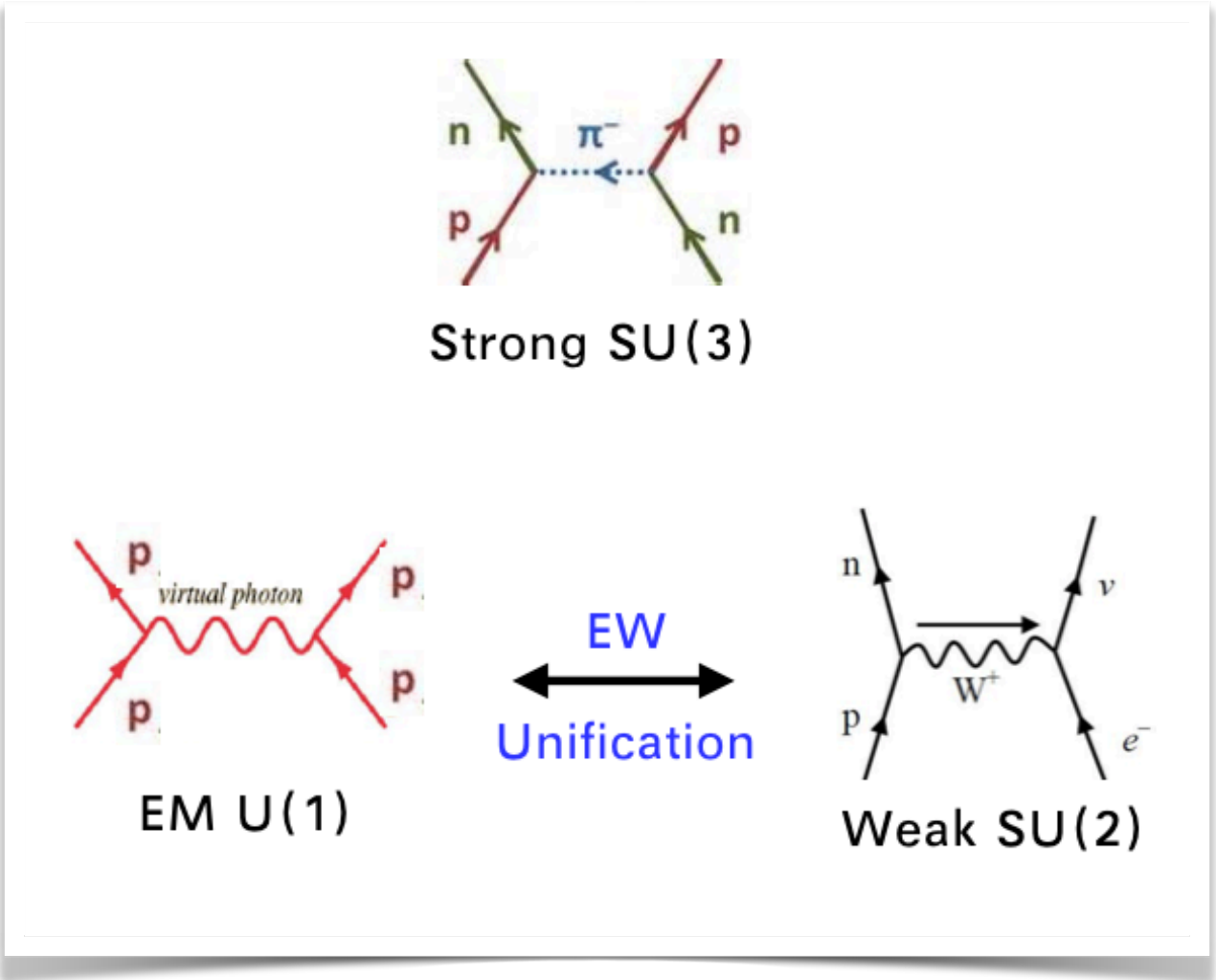
Standard model of particle physics

17 elementary particles



All discovered

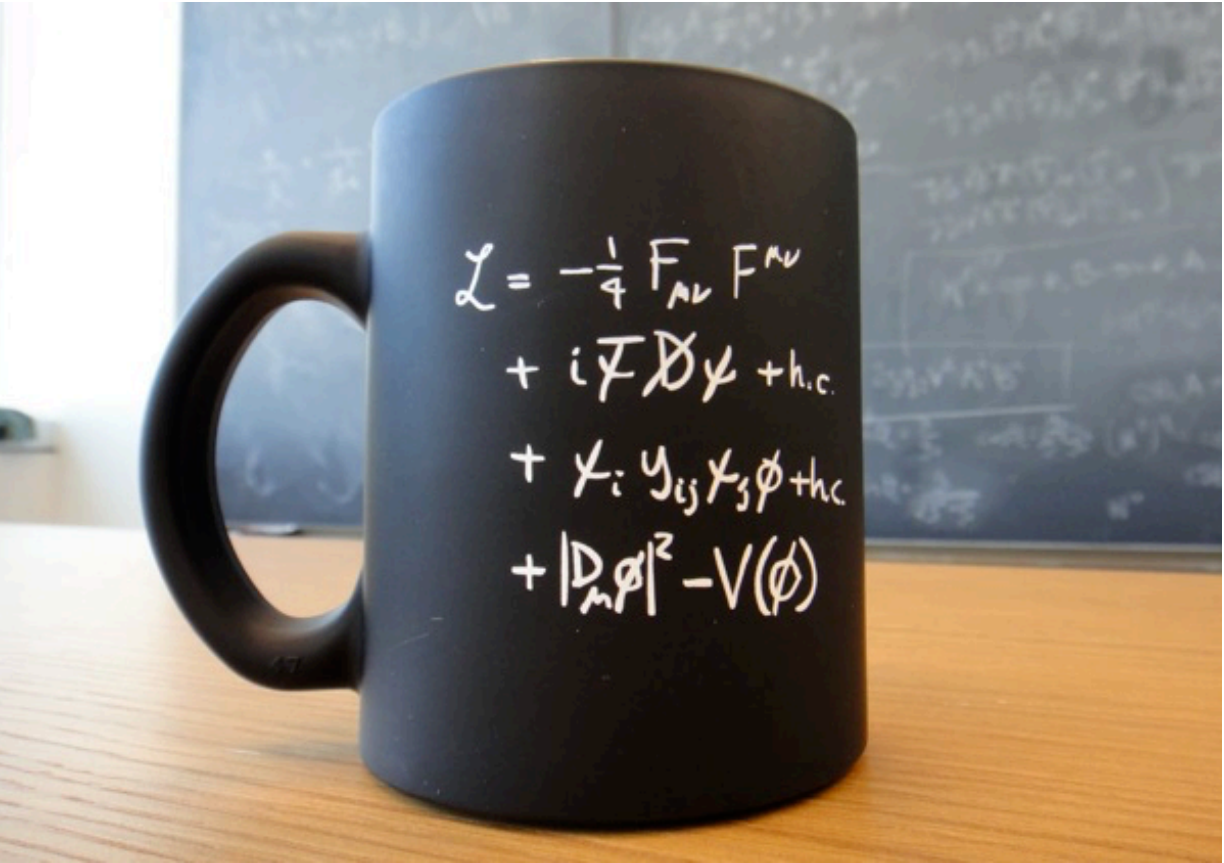
3 kinds of interactions



All found, also

EW SSB verified

18 parameters (massless neutrino)



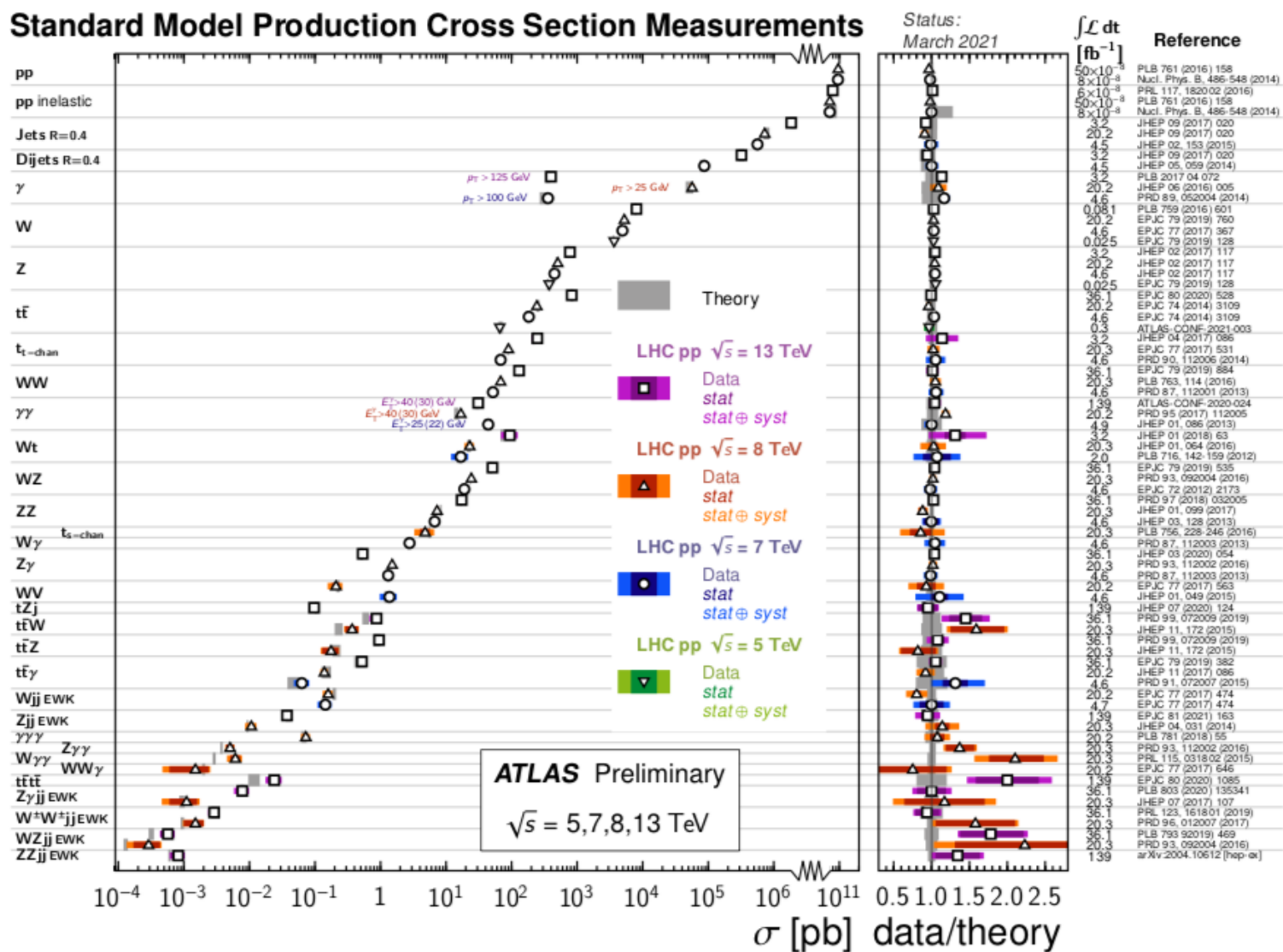
All known,

3 gauge couplings + 2 Higgs potential
+ 12 Yukawa + 1 CPV

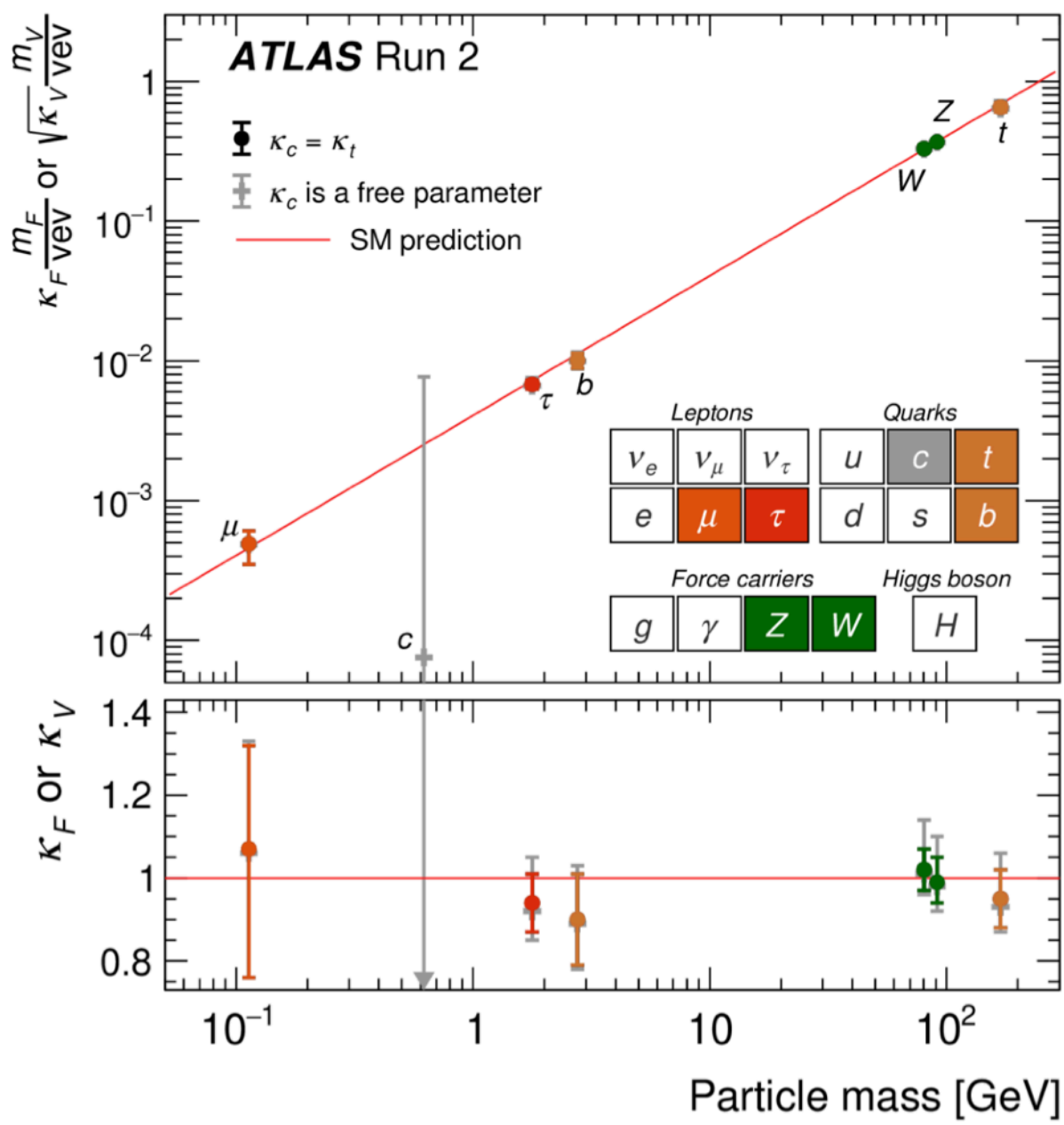
17+9 =	1	1	1	1	9+3	4	6
formal:	g	g'	v	λ	λ_f	V_{CKM}	U_{PMNS}
practical:	α	M_W	M_Z	M_H	m_f		

Precision measurements

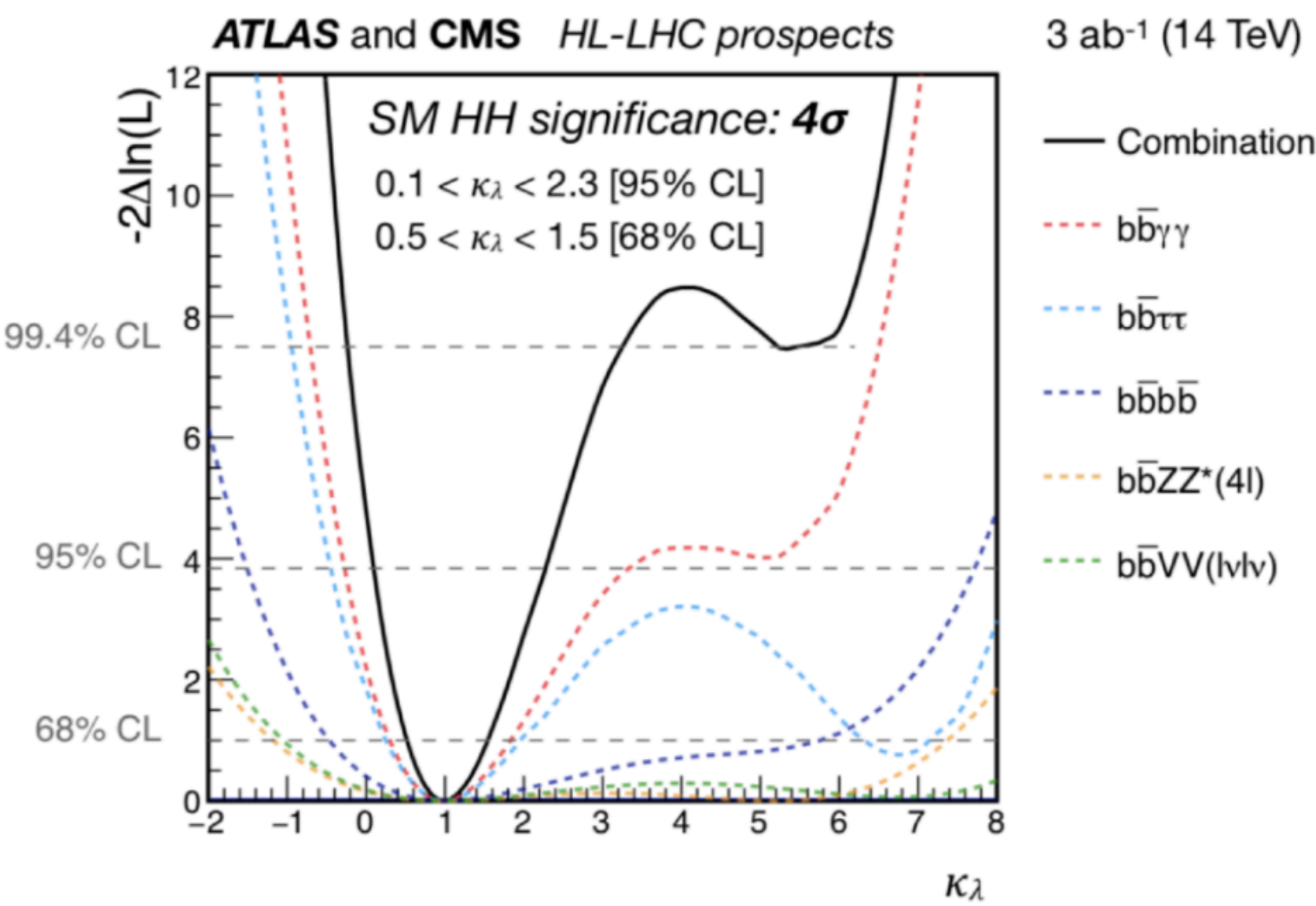
Validation of the SM predictions



light-flavor Higgs coupling?



Higgs self coupling?



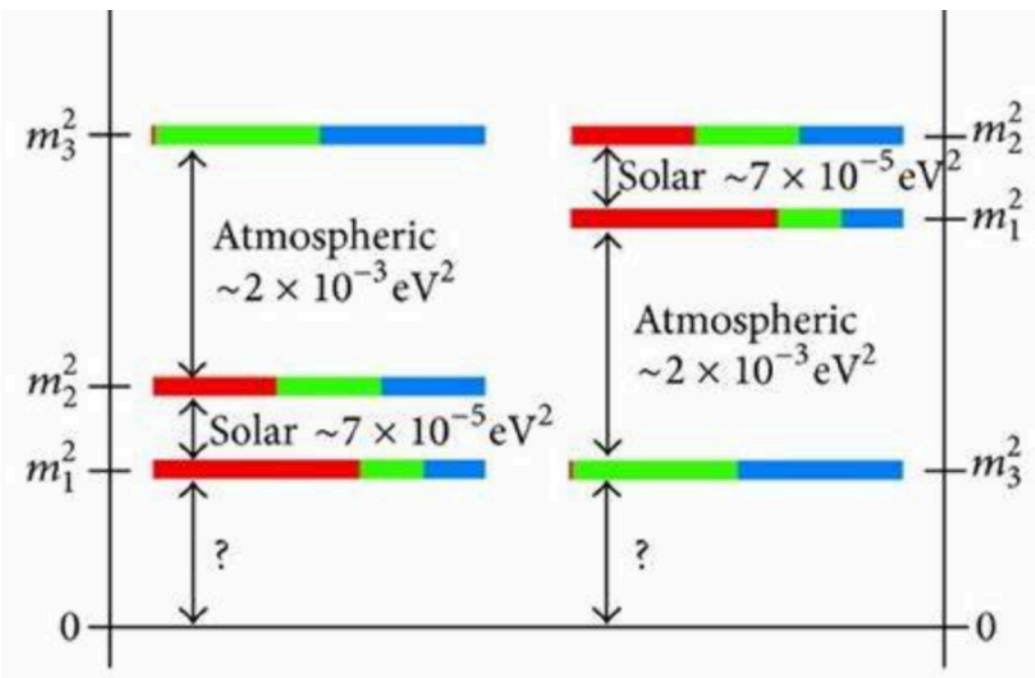
Neutrino parameters and measurements

Additional 7(9) Yukawa parameters exist if Dirac (Majorana) neutrino masses are non-zero

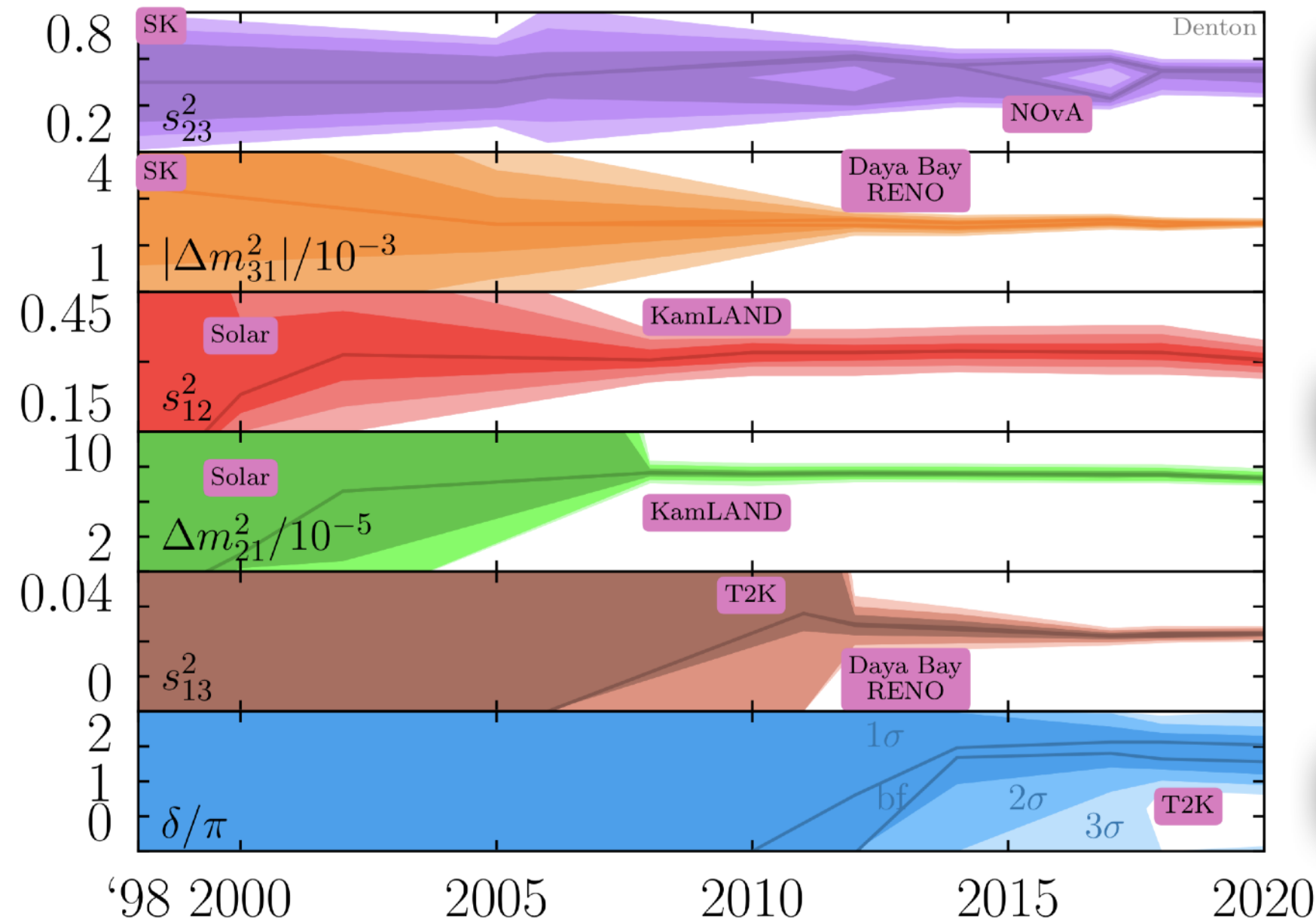
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \text{ \& } \Delta M^2_{32}$ CP phase δ & θ_{13} $\theta_{12} \text{ \& } \Delta M^2_{21}$ Majorana phase

Atmospheric accelerator reactor accelerator solar reactor Double beta decays



Normal or Inverted hierarchy



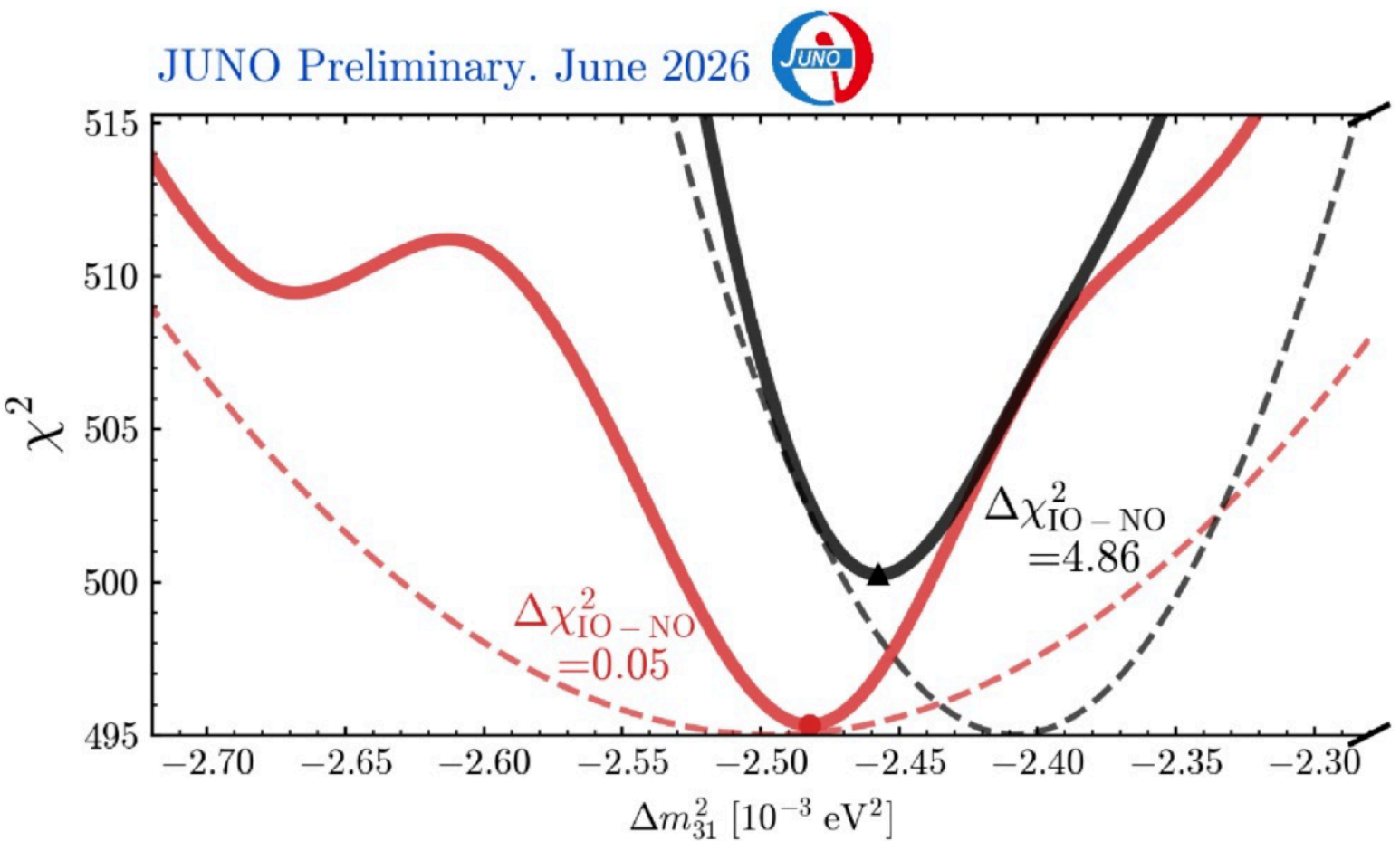
• θ_{23} octant

• Mass ordering ($|\Delta m^2_{23}| \rightarrow \Delta m^2_{23}$)

Absolute mass

• CP phase (δ)

If Majorana, 3 CP phases

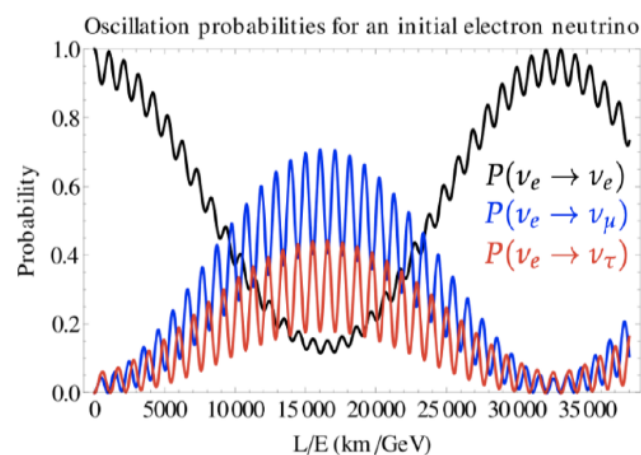


Motivation for new physics

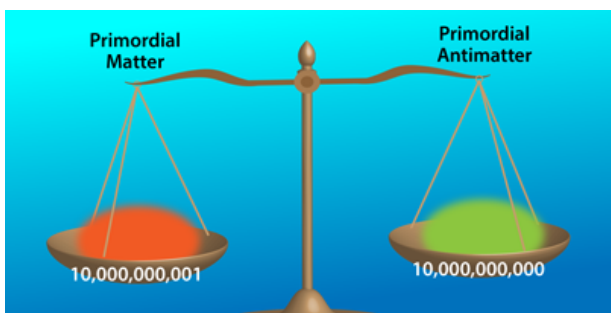
There are experimental challenges in the standard model and theoretical motivation for new physics

experimental challenges

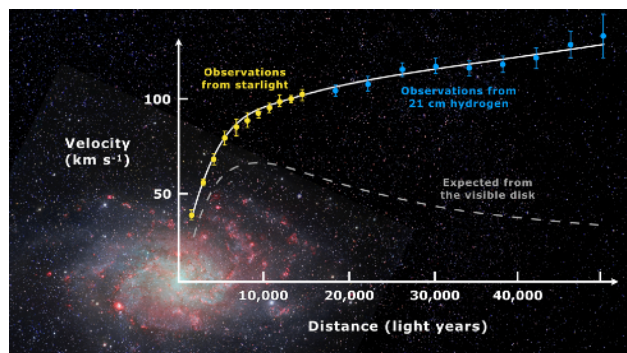
Neutrino masses



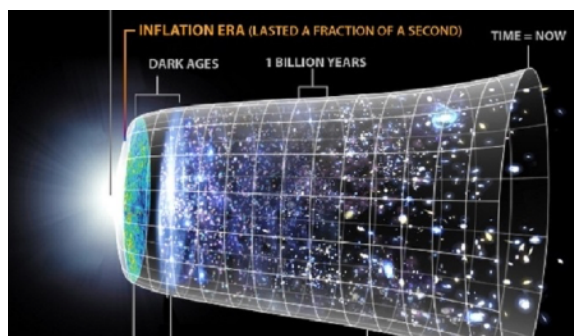
Baryon asymmetry



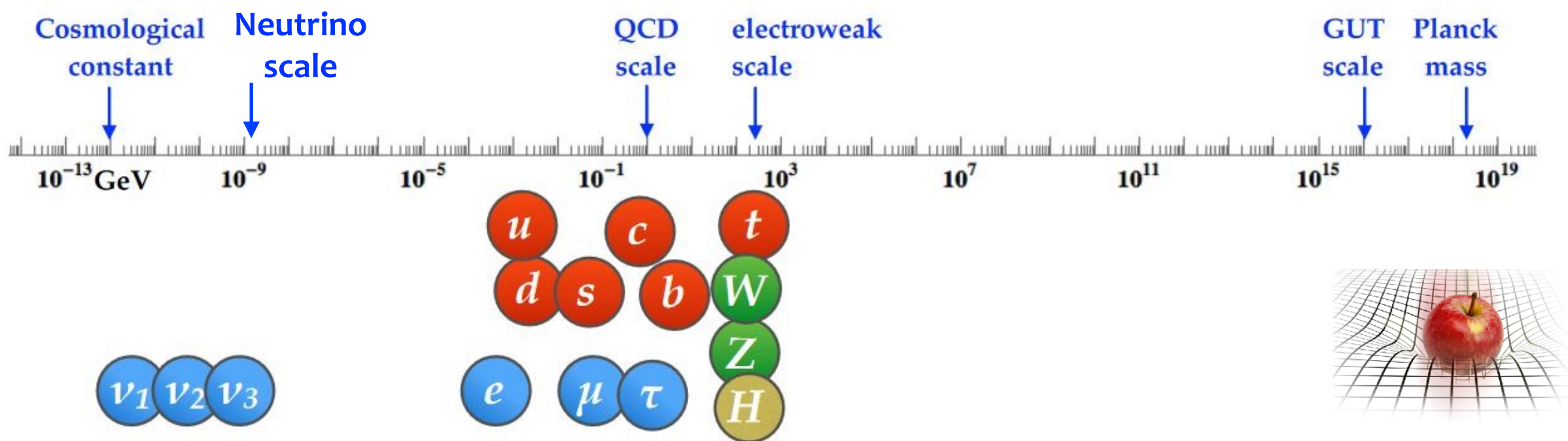
Dark matter



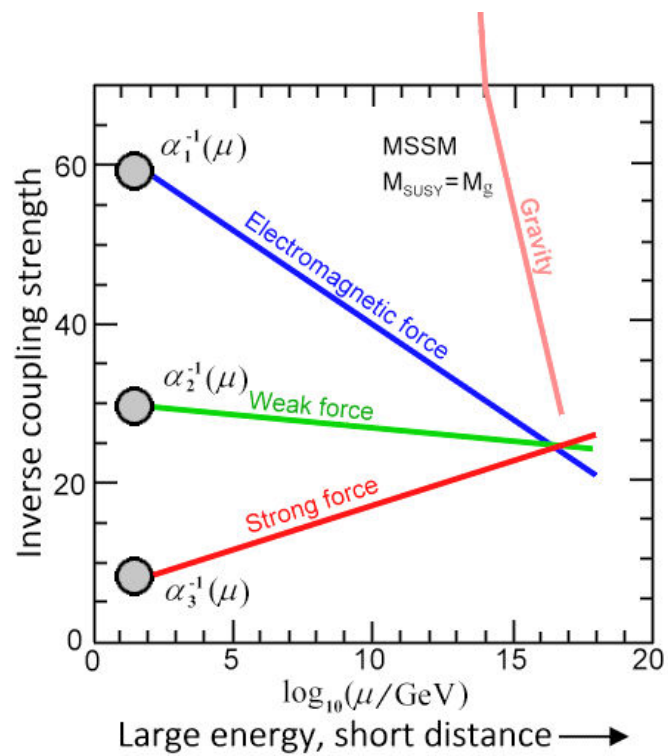
Inflation



theoretical motivation

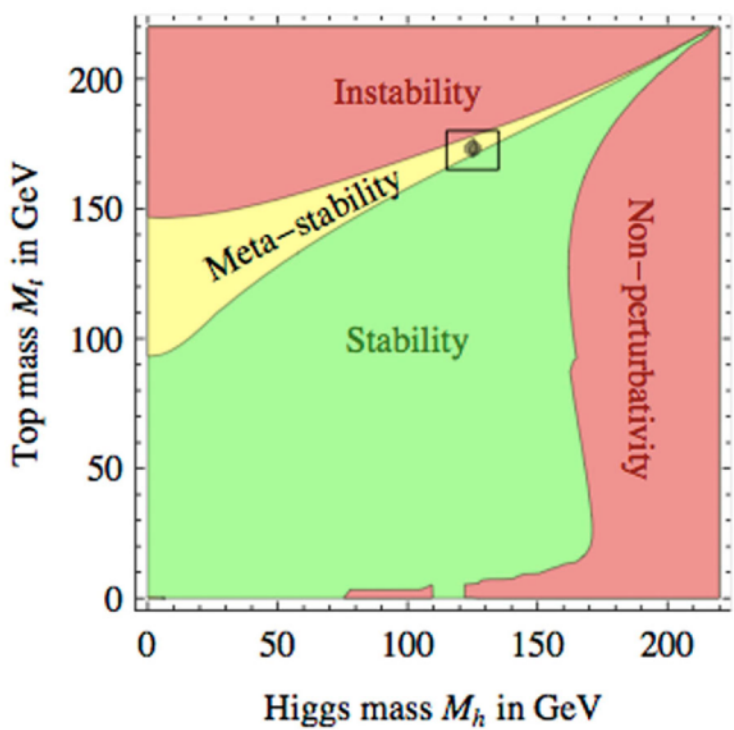


Fermion flavor hierarchy



Gauge unification

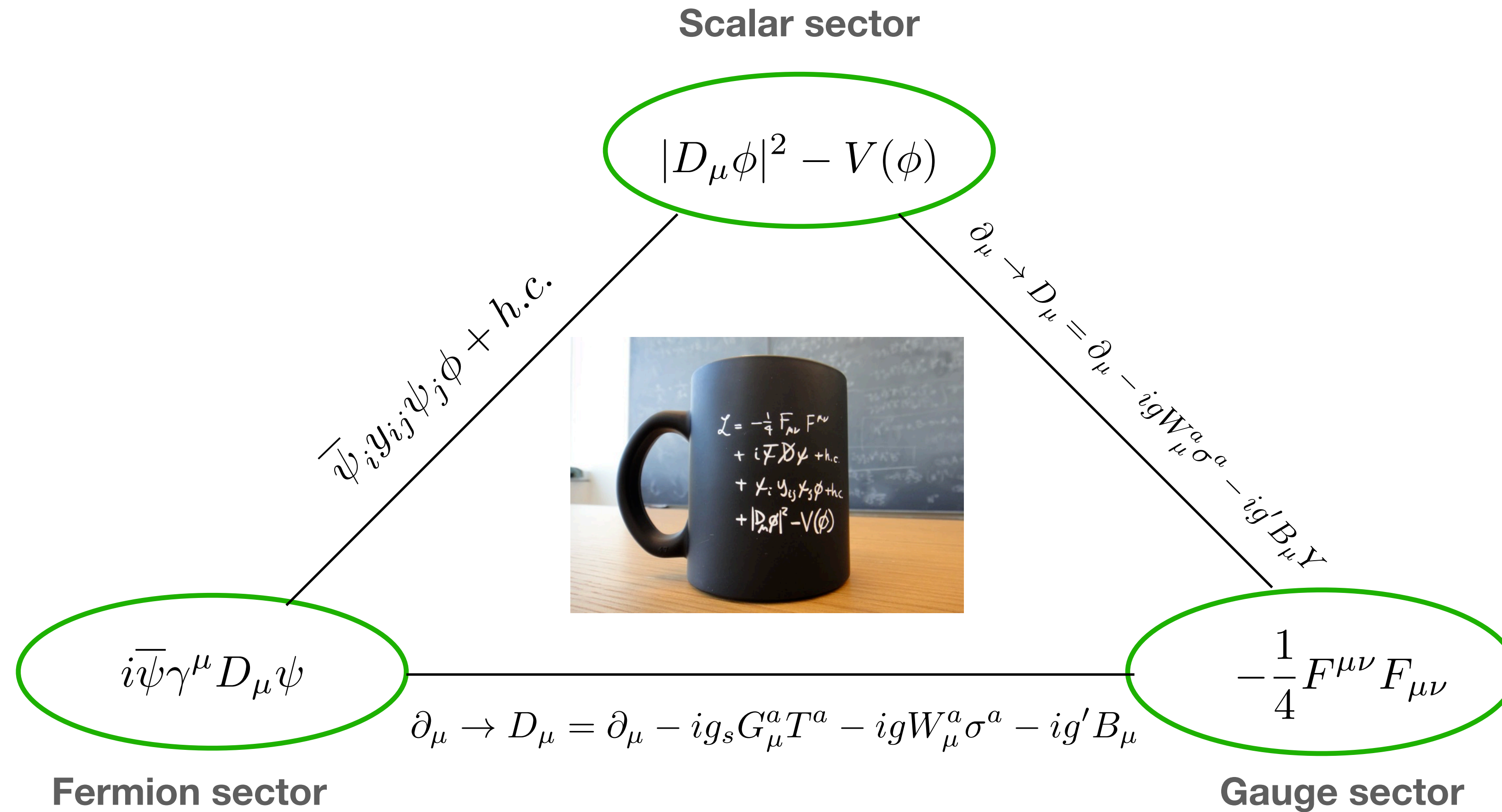
Higgs hierarchy problem



Vacuum stability

New Physics Model Building

Extension of the standard model

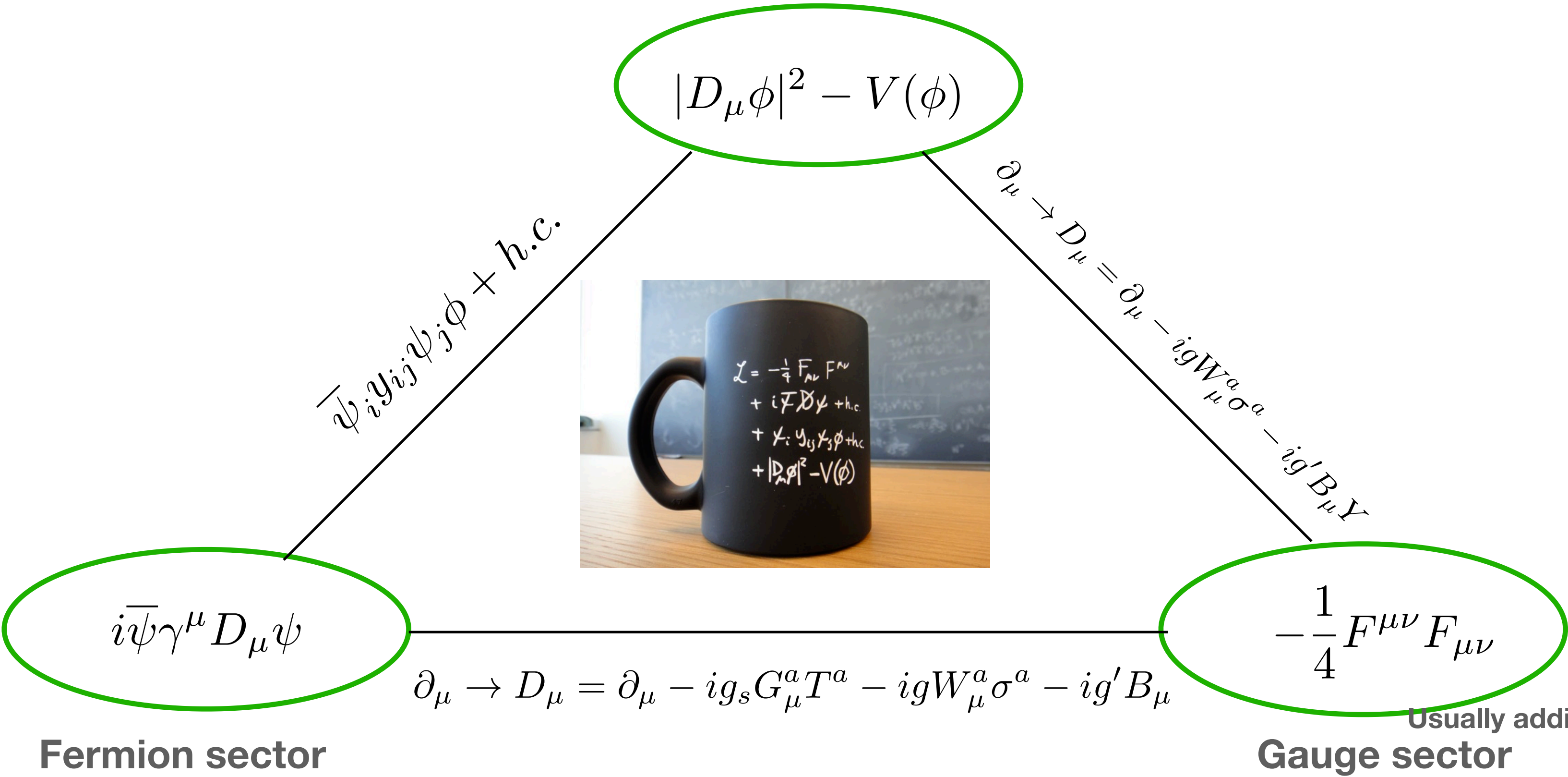


Simplified new physics models

Scalar Extension: SM + real or complex scalar

Scalar sector

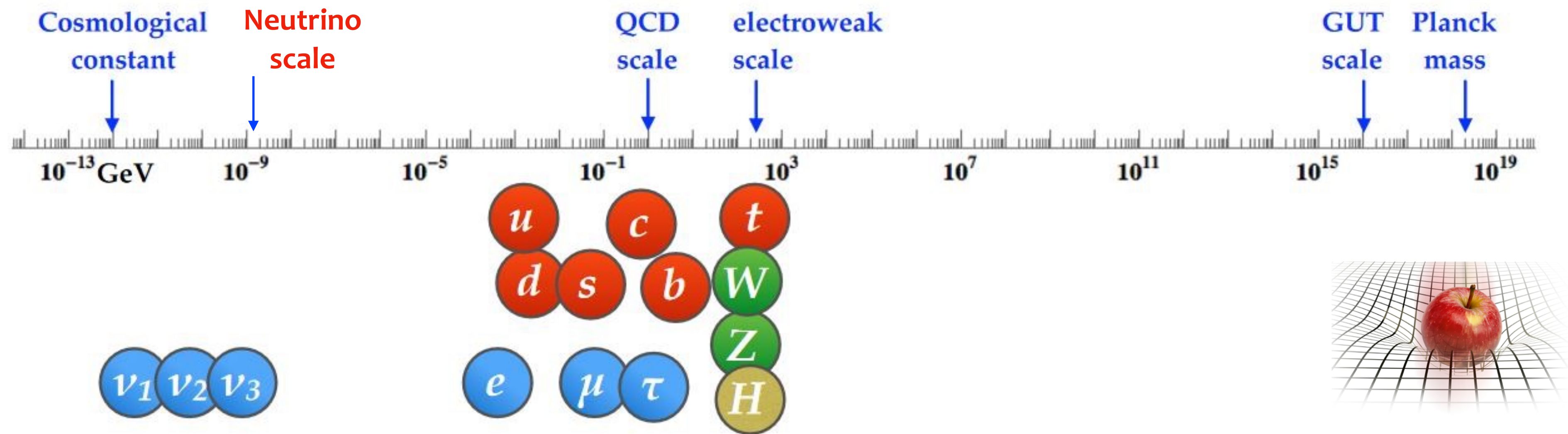
singlet, doublet, triplet, ...



Fermion Extension: SM + vector-like fermion
singlet, doublet, triplet, ...

Gauge Extension: SM + U(1), SU(2), SU(3) = G211, G221, G311
SU(4) Pati-Salam, SU(5) GUT, SO(10), ...

Hierarchy problem



Why neutrino masses so tiny?

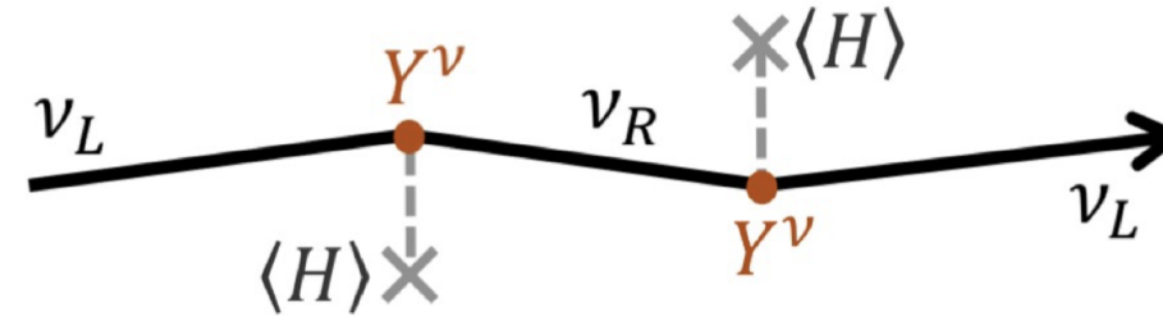
Why Higgs mass so light?

Majorana neutrino

Introduce Majorana neutrino to explain small neutrino masses

Dirac neutrino

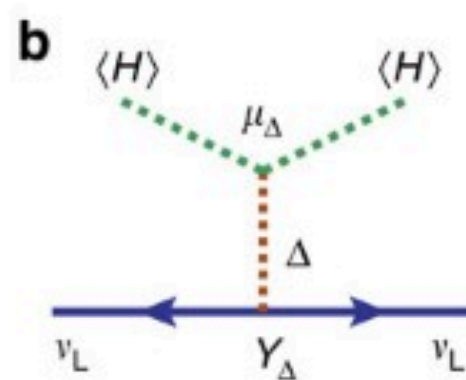
$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix}$$



$$\mathcal{L}_m = \underbrace{m_D \bar{\psi}_R \psi_L}_{\text{Dirac term}} + \underbrace{\frac{1}{2} m_L \bar{\psi}_L^c \psi_L + \frac{1}{2} m_R \bar{\psi}_R \psi_R^c}_{\text{Majorana terms}} + \text{h.c.}$$

Type-II seesaw

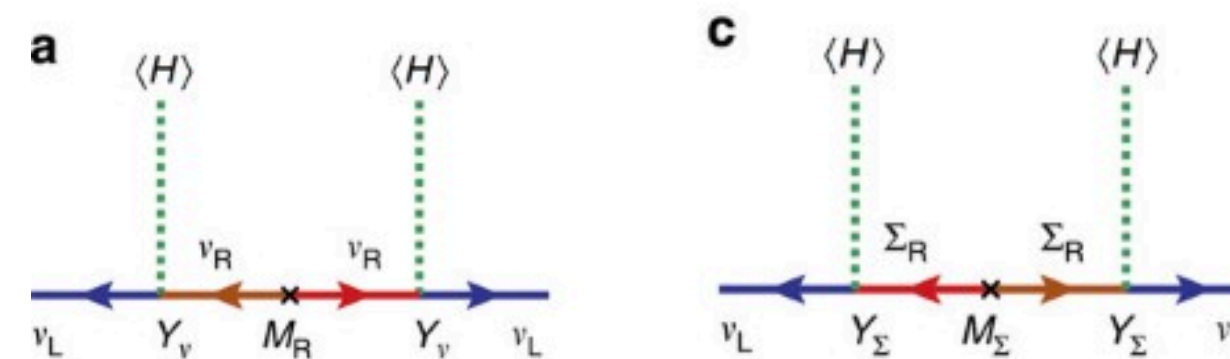
$$\mathbf{M} = \begin{pmatrix} m_L & 0 \\ 0 & 0 \end{pmatrix}$$



$$M_\nu = \langle H \rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

Type-I and III seesaw

$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

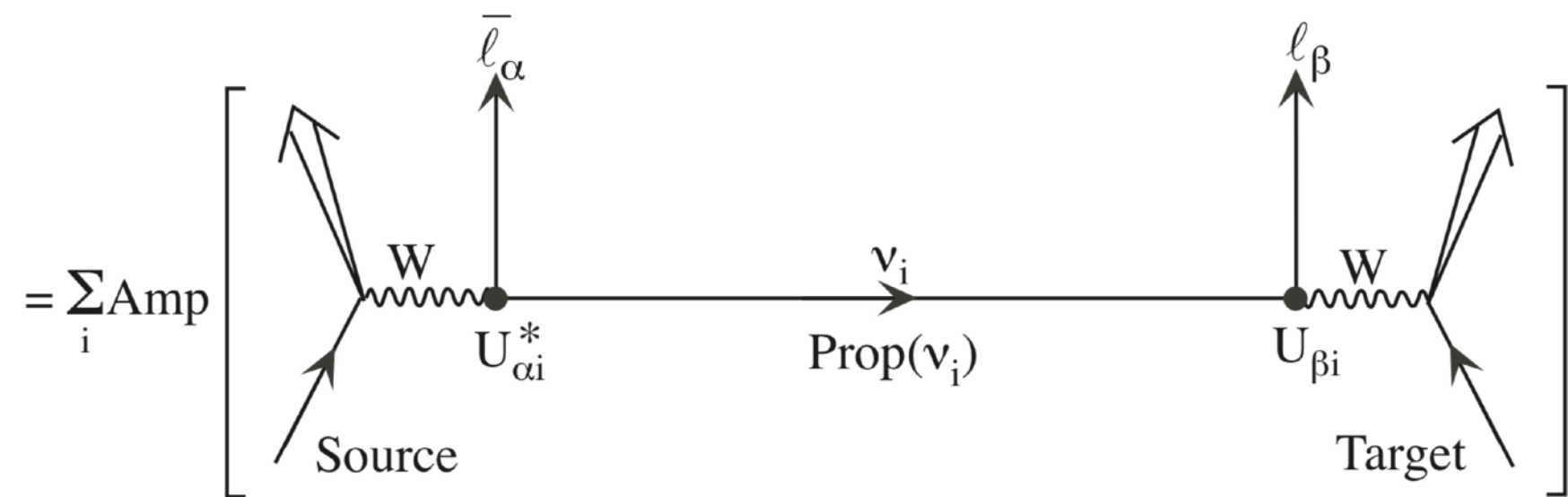
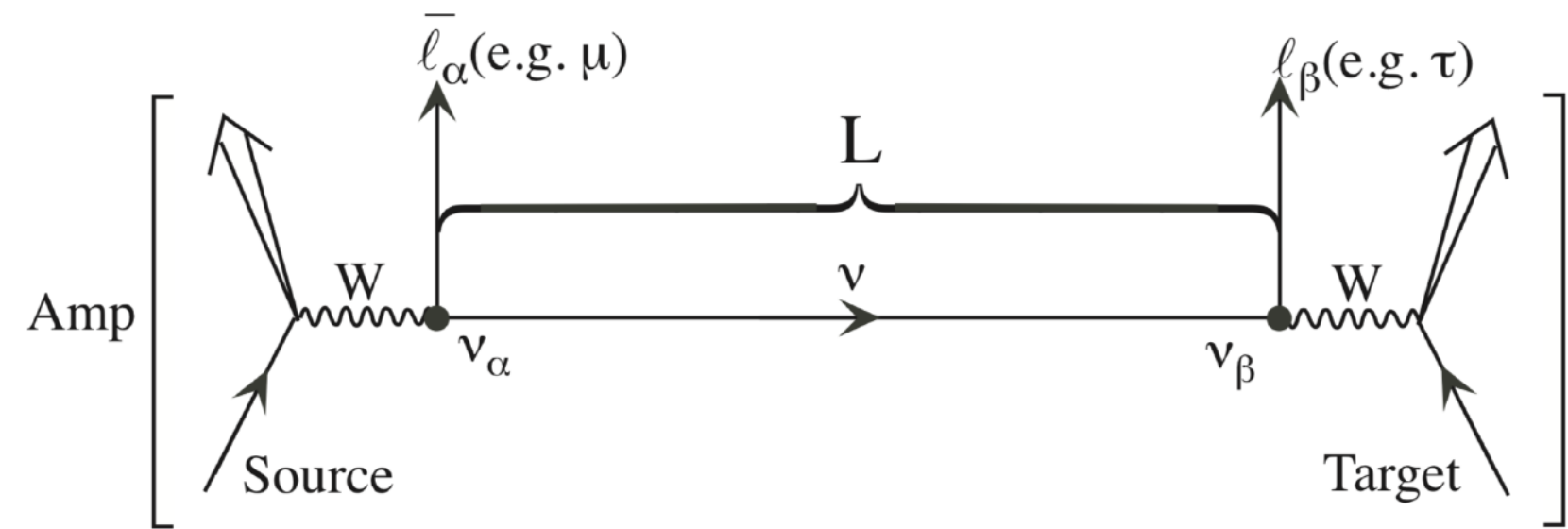


$$m_\nu = \frac{(Y^\nu v_{EW})^2}{m_R}$$

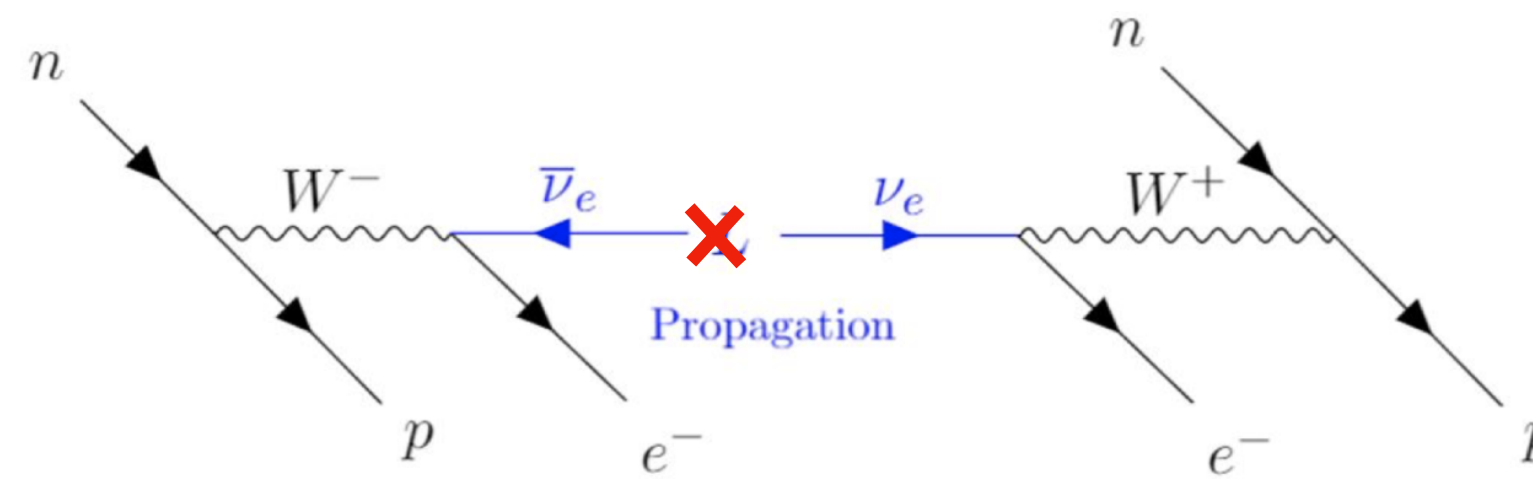
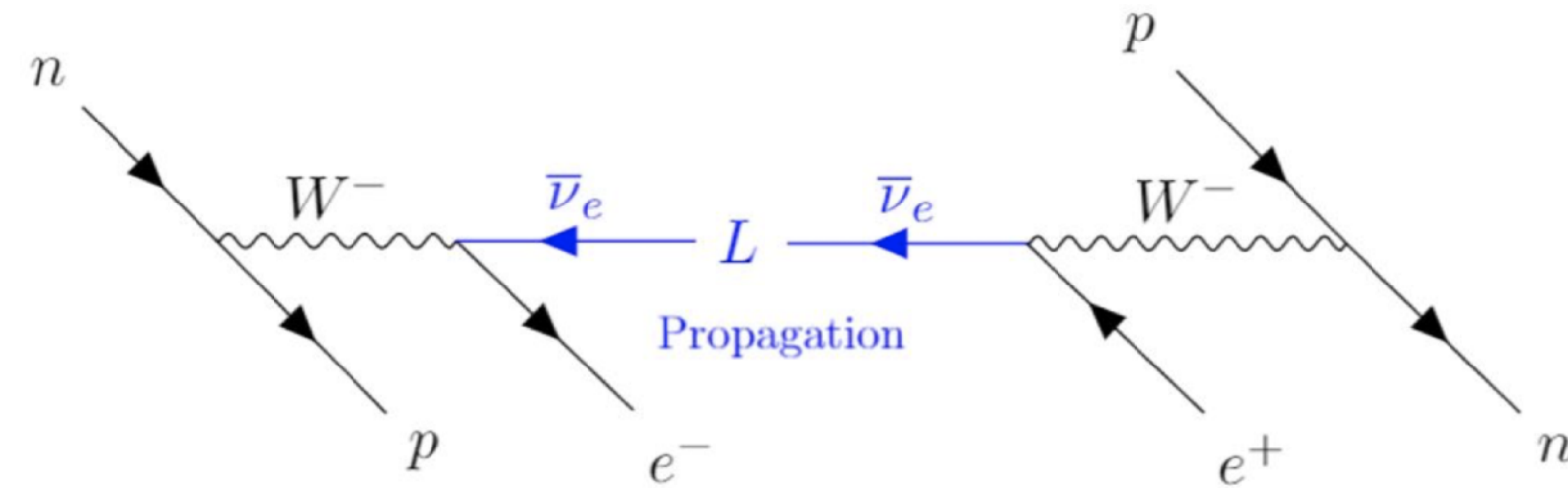
[Zhi-Zhong Xing, Xiao-Gang He, Yi Liao, Shao-Long Chen, Shun Zhou, Gui-Jun Ding, Shao-Feng Ge, Xun-Jie Xu ...]

Majorana or Dirac

Compared to Dirac neutrino propagation (oscillation), Majorana propagation is suppressed by a factor m_ν^2/E^2



$$\text{Amp}(\nu_\alpha \rightarrow \nu_\beta) = \sum_{i=1}^3 U_{\alpha i}^* e^{-i \frac{m_i^2}{2E} L} U_{\beta i}$$



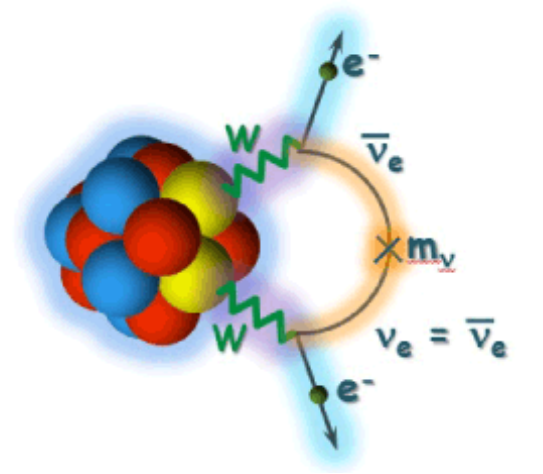
$$u_L = \frac{1}{2} (1 + \kappa) u_\uparrow + \frac{1}{2} (1 - \kappa) u_\downarrow,$$

$$\kappa \sim \left(1 - \frac{m}{E}\right).$$

$$\frac{1}{2}(1 - \kappa) \sim \frac{m}{E}$$

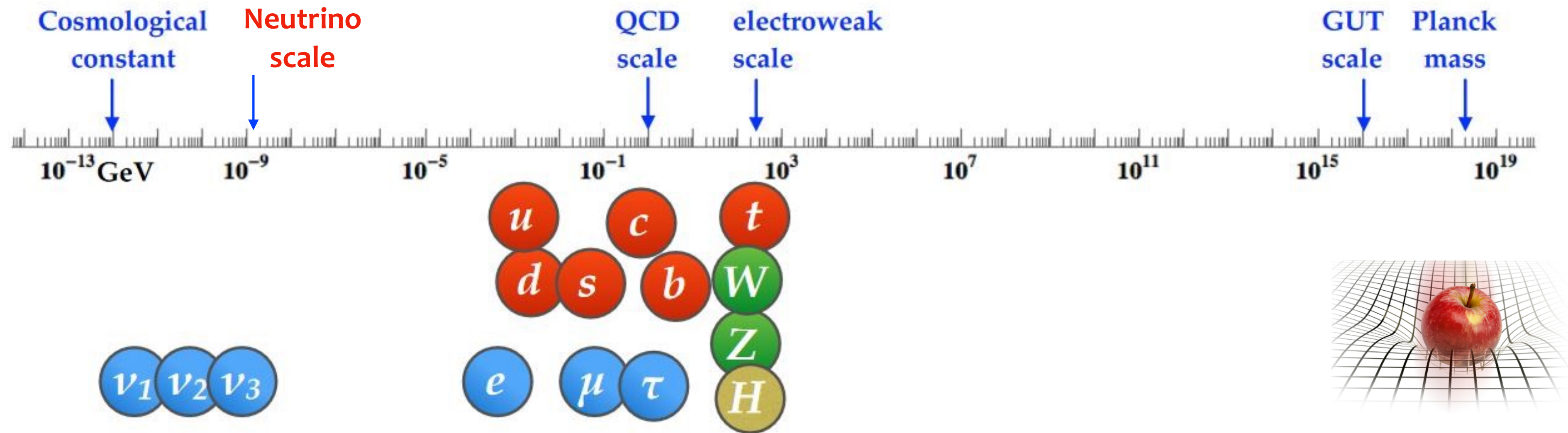
$$\mathcal{M} = \mathcal{A} \sum_i (U_{ei})^2 m_{\nu_i} = \mathcal{A} m_{\beta\beta}$$

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_1 e^{2i\lambda_a} + s_{12}^2 c_{13}^2 e^{2i\lambda_b} \sqrt{m_1^2 + \Delta m_{12}^2} + s_{13}^2 \sqrt{m_1^2 \pm |\Delta m_{23}^2|}.$$



The lower energy, the better: 0νbb!

Hierarchy problem



Why neutrino masses so tiny?

Why Higgs mass so light?

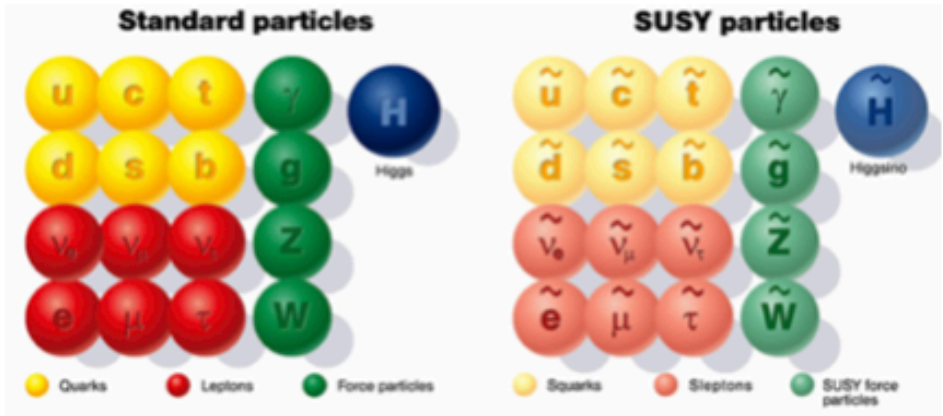
Simplified models cannot solve hierarchy problem

Beyond simplified model

Introduce new symmetry for the Higgs boson

Supersymmetry

$$H \leftrightarrow \tilde{H}$$



Higgs Higgsino

MSSM, NMSSM,
vMSSM, TMSSM, ...

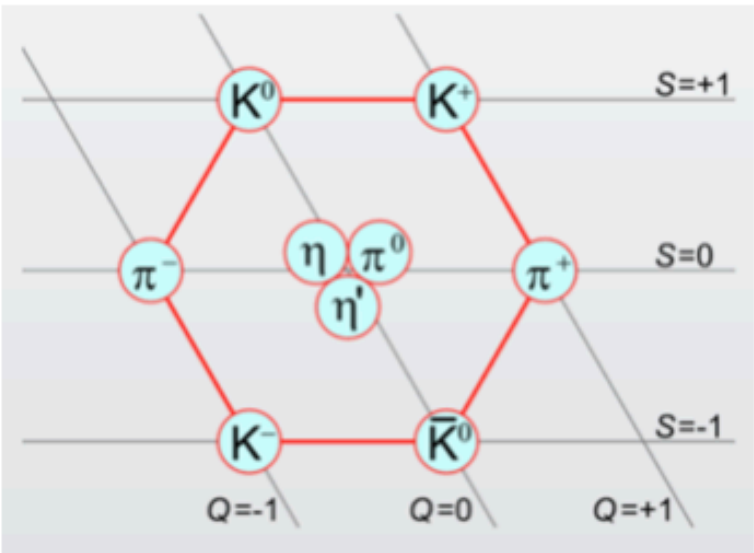
Gravity mediation
Gauge mediation
Anomaly mediation

...

Hierarchy
Problem
Solutions

Composite Higgs

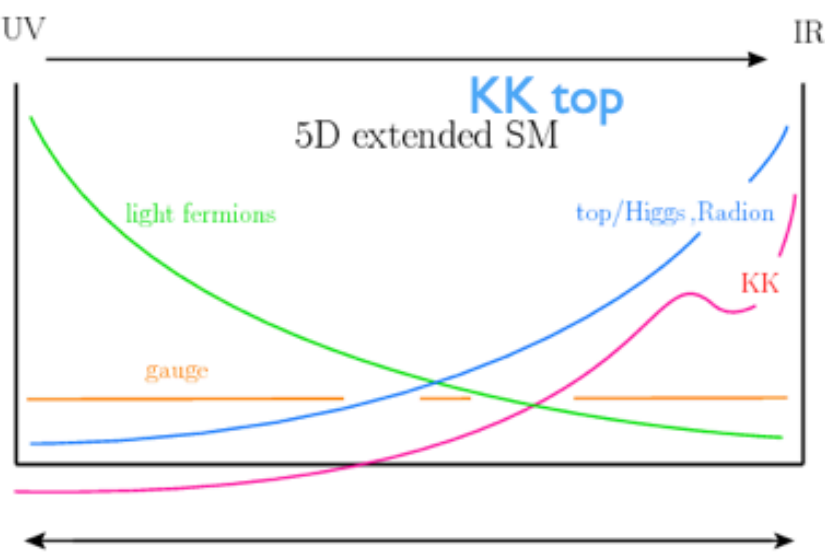
$$\text{shift: } h \rightarrow h + a$$



Higgs similar to pion

Extra Dimension

$$\text{Conformal: } h \rightarrow e^\omega h$$



Higgs as 5D gauge boson

ADD model
Randall-Sundrum
Higgsless
Soft-wall
Flavor XD

...

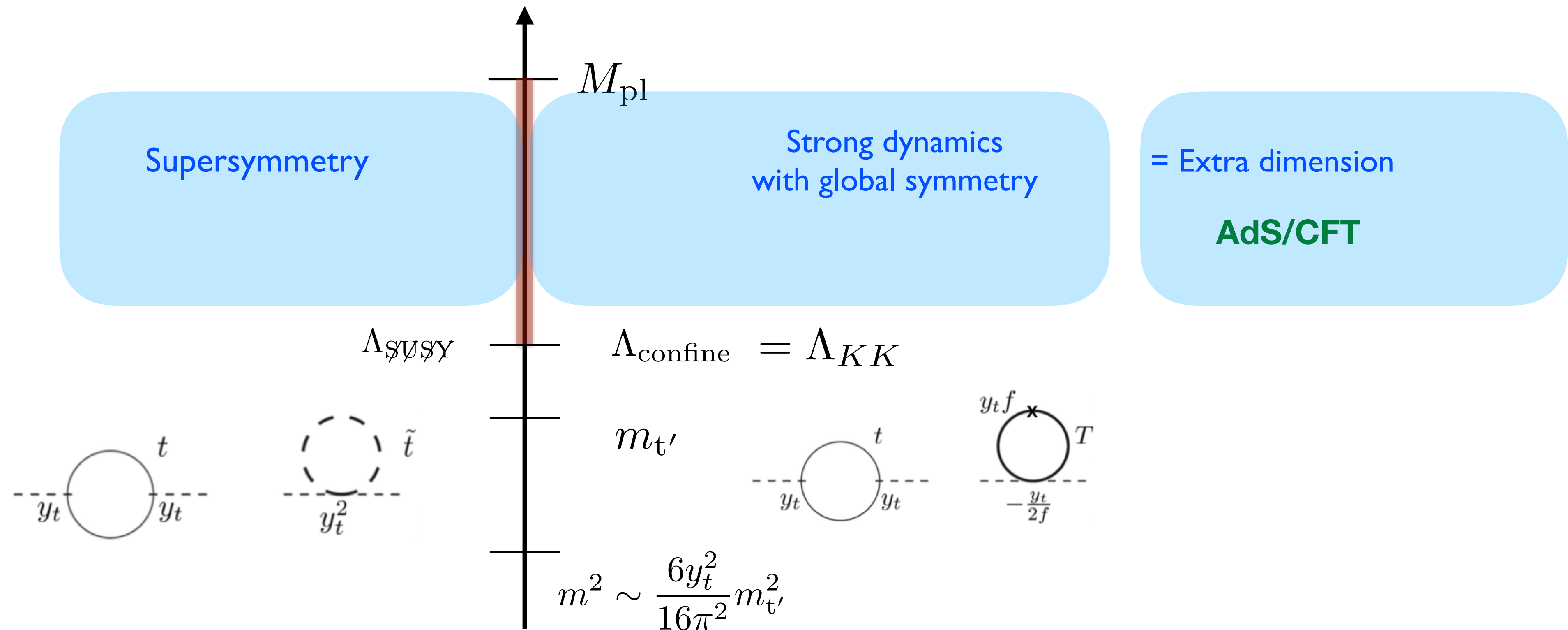
Technicolor
Little Higgs
Minimal Composite Higgs
Twin Higgs
Neutral naturalness

...

[Hong-Jian He, Jin-Min Yang, Tian-Jun Li, Chun Liu, Qing Wang, Chong-Xing Yue, Qing-Hong Cao, Tao Liu, Jing Shu, Jun-Jie Cao, Yue Zhao, Hong-Hao Zhang, Hao Zhang, Jing Ren, Jia-Ying Gu, Zhe-Wei Yin, J.-H. Yu, ...]

Smoking gun signature

Little hierarchy problem: A light top partner is needed to cancel quadratic divergence of top quark loop

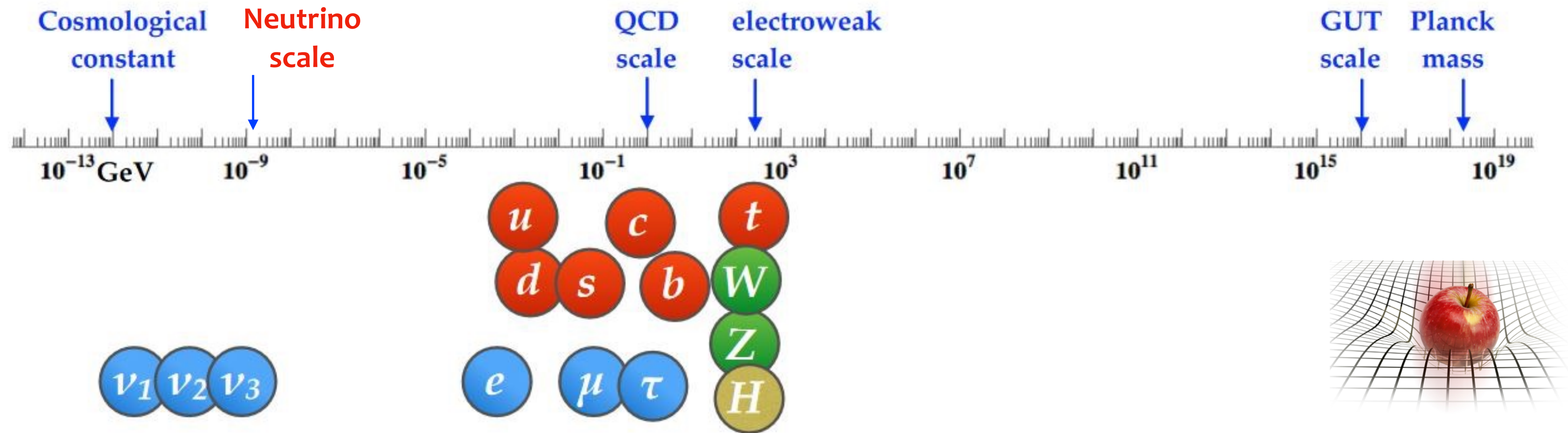


Unlike simplified models, usually solve several problems at the same time

Matter-antimatter asymmetry

Dark matter candidates

Baryon asymmetry



Why neutrino masses so tiny?

Leptogenesis

Why Higgs mass so light?

Electroweak baryogenesis

[M. Ramsey-Musolf, Xin-min Zhang, Tao Liu, Jing Shu, Wei Chao, Cheng-Cheng Han, Zhen-Hua Zhao, Ke-Pan Xie, J.-H. Yu, ...]

Light new particles

Hierarchy problem for QCD CP phase

$$\bar{\theta} = -\arg \det [e^{-i\theta} y_u y_d]$$

$$\delta_{CKM} = \arg \det [y_u y_u^\dagger, y_d y_d^\dagger]$$



$$\bar{\theta} \lesssim 10^{-10}$$

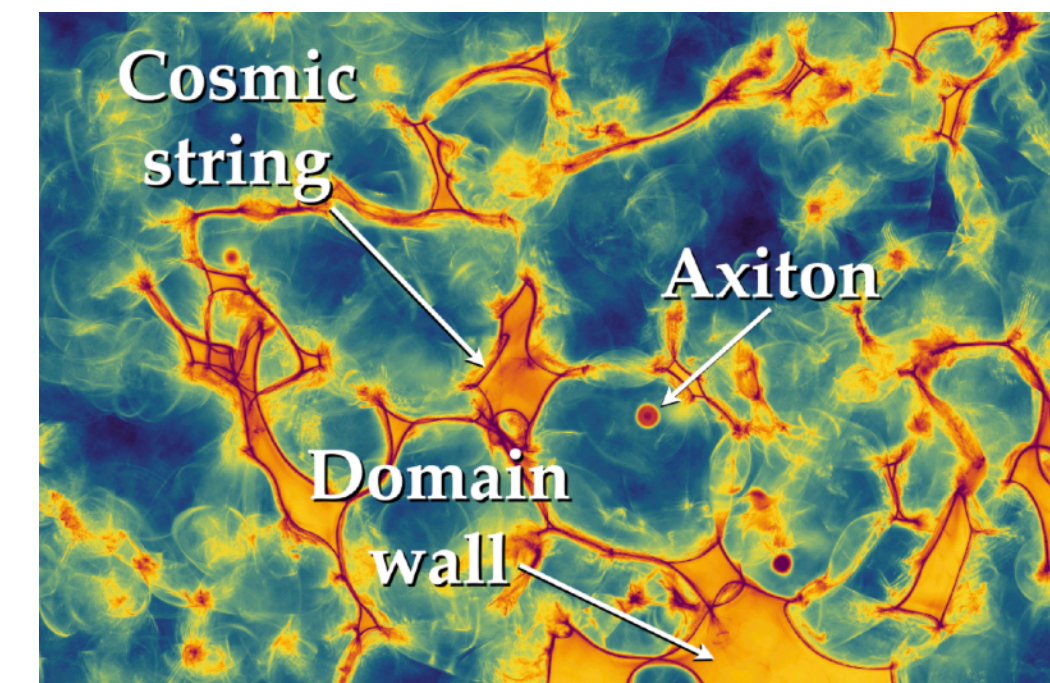
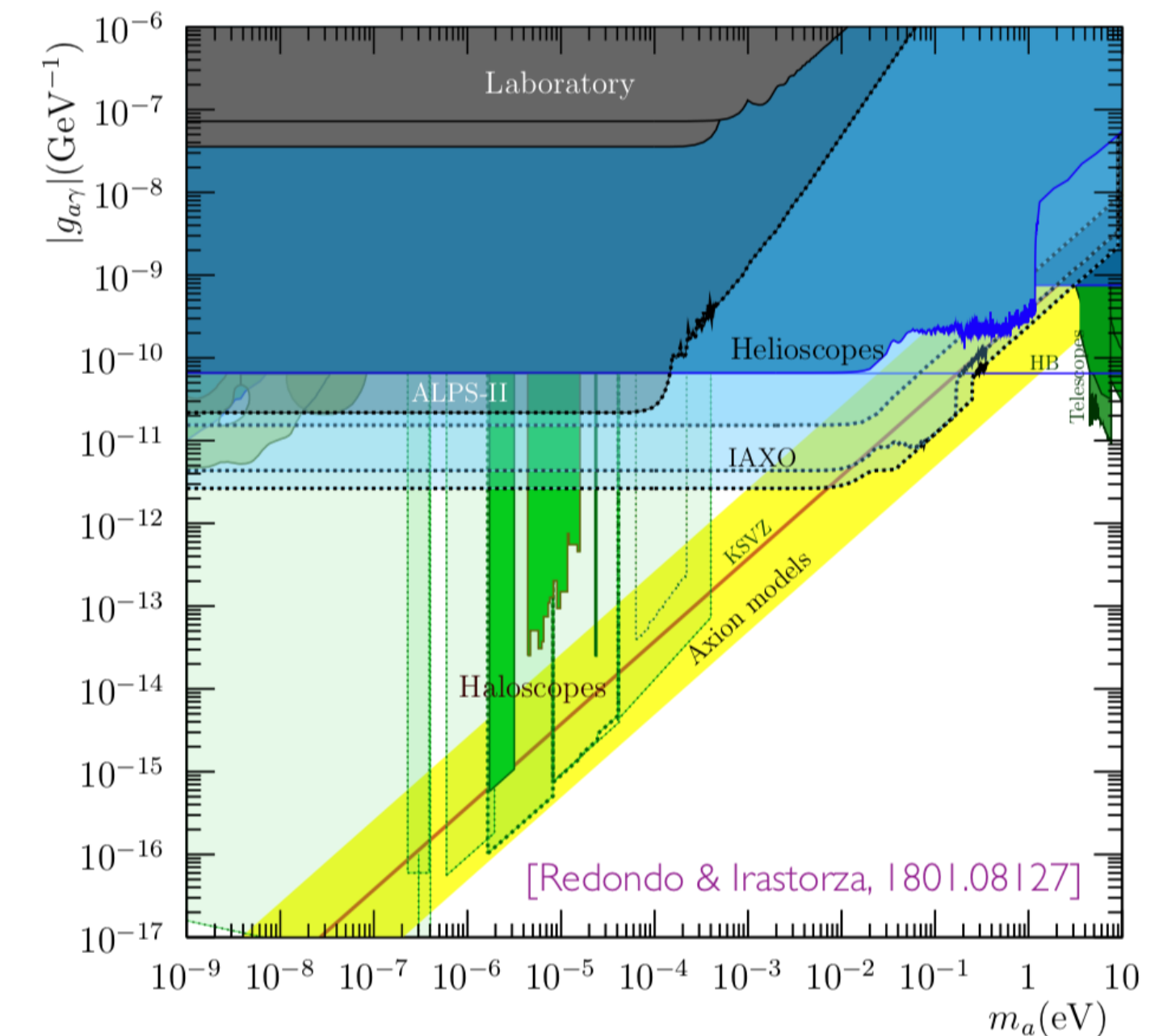
$$\delta_{CKM} \simeq \mathcal{O}(1)$$

- assume a global $U(1)_{PQ}$: i) QCD anomalous and ii) spontaneously broken
- axion: PGB of $U(1)_{PQ}$ breaking

anomalous PQ breaking (fermion sector) + spontaneous PQ breaking (scalar sector)

[Tian-Jun Li, Jia Liu, Qiaoli Yang, Yu Gao, Chen Sun, Zhi-Hui Guo, J.-H. Yu, ...]

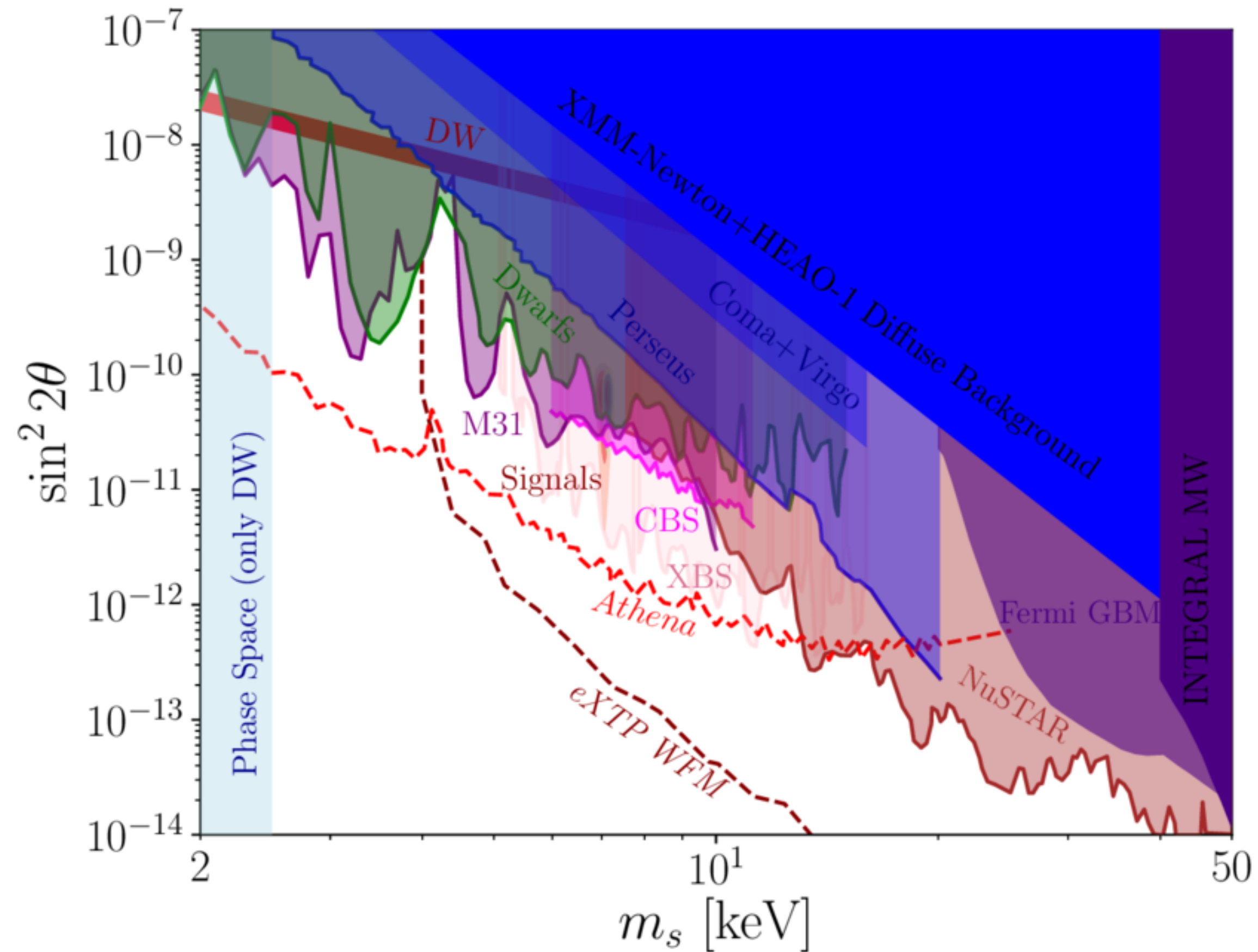
Axion search limits



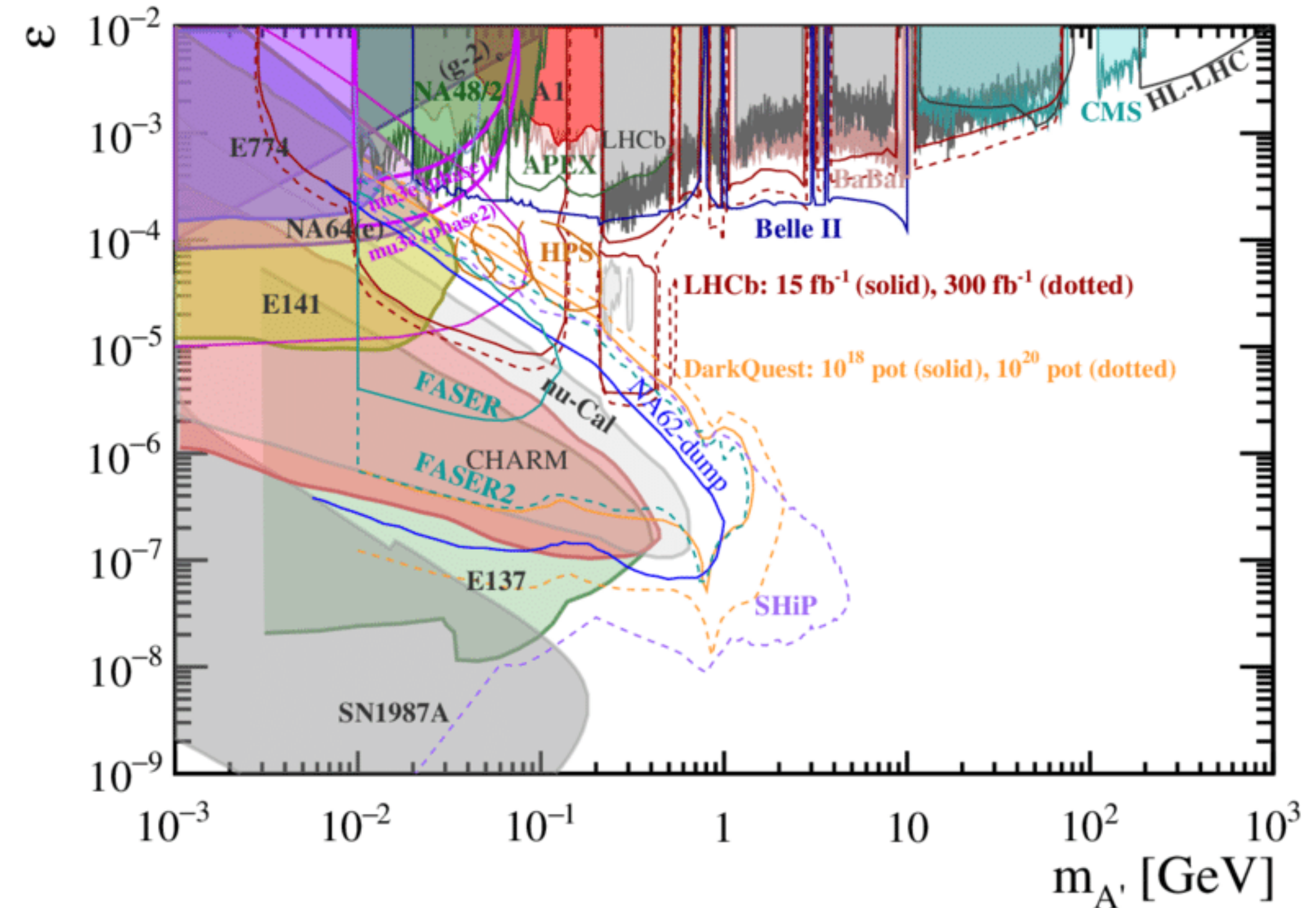
[Li-Gong Bian, Huai-Ke Guo, Fa Peng Huang, Ye-Ling Zhou, Yun Jiang, Zhao-Huan Yu, ...]

Light new particles

Light sterile neutrino searches



Sub-GeV dark photon searches

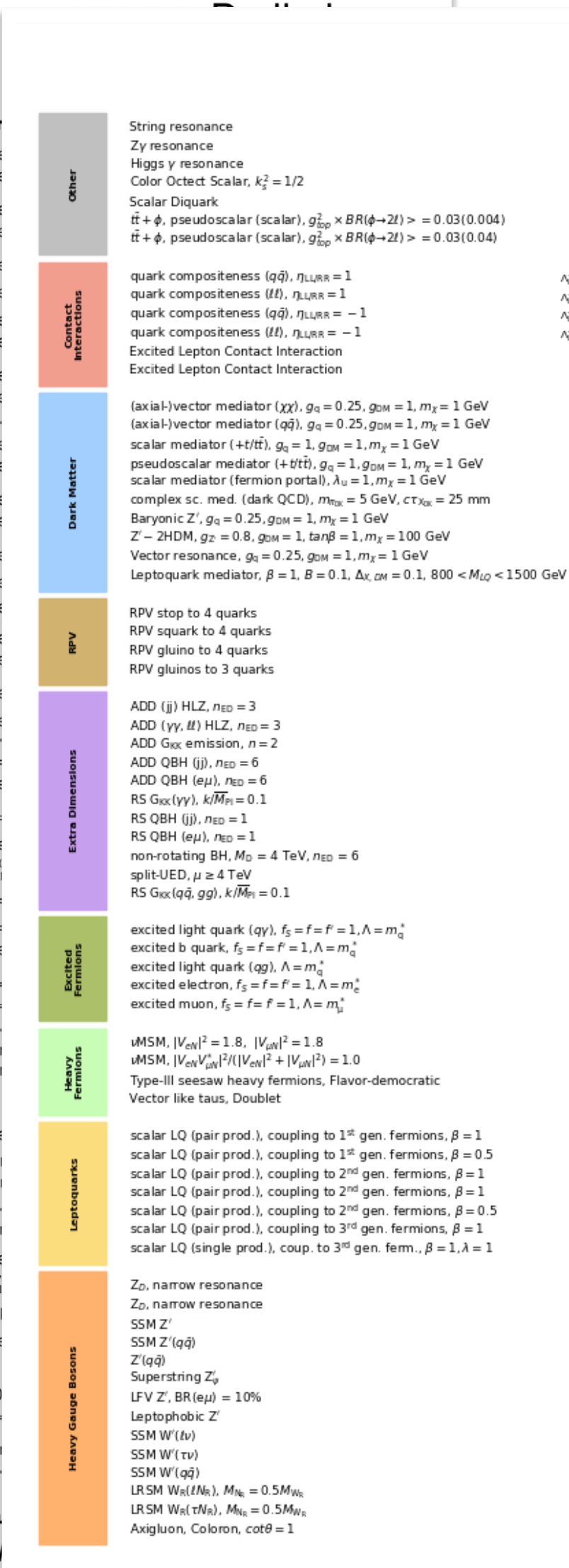
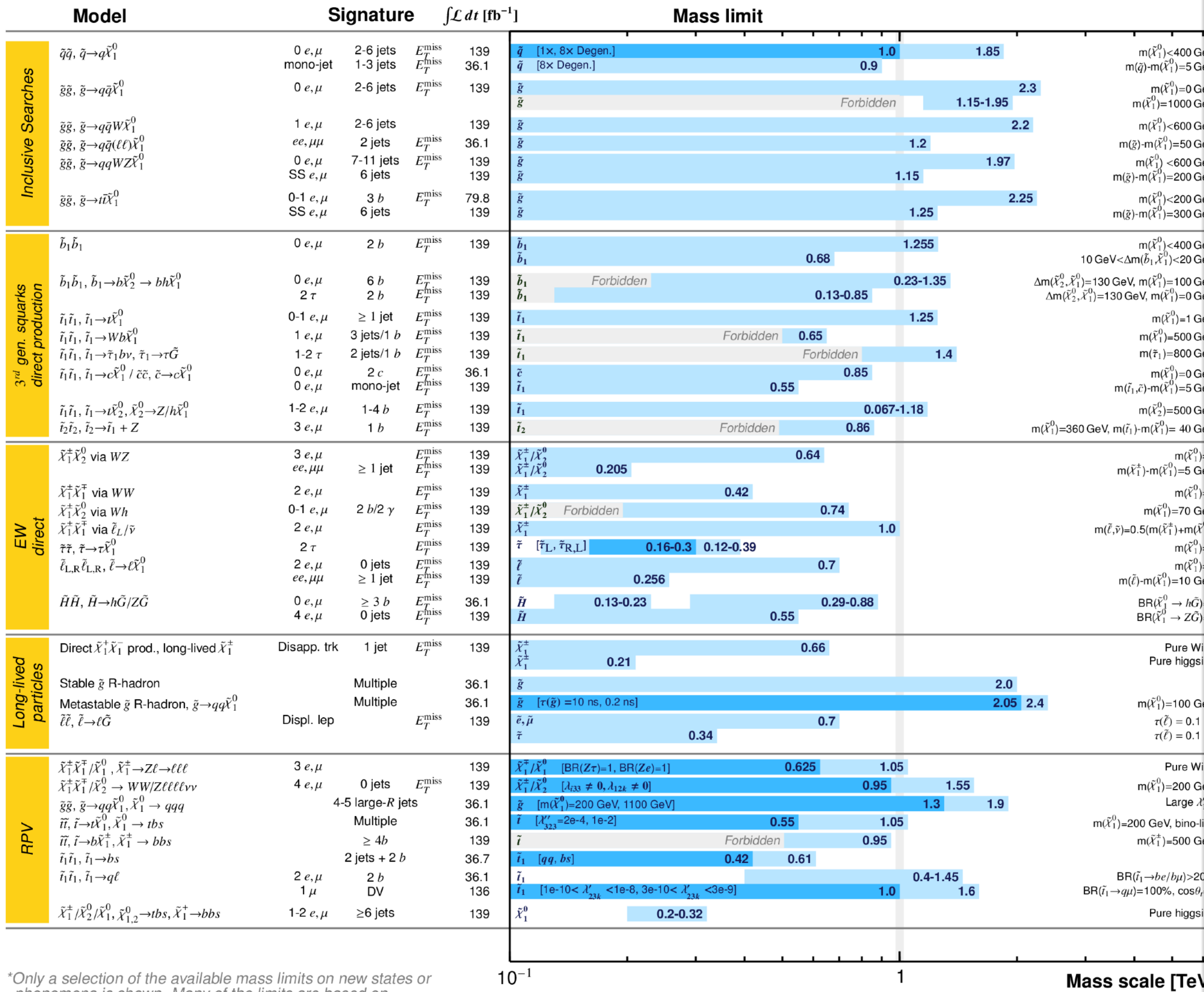


[Hai-Peng An, Xiao-Gang He, Yue-Liang Wu, Yu-Feng Zhou, Jing Shu, Zuo-Wei Liu, Lei Wu, Yue Zhao, Yong Tang, Xiao-Ping Wang, Yong-Chao Zhang, Wei Su, Ning-Qiang Song, Peizi Du, Da Liu, Sida Lu, ...]

TeV new physics searches

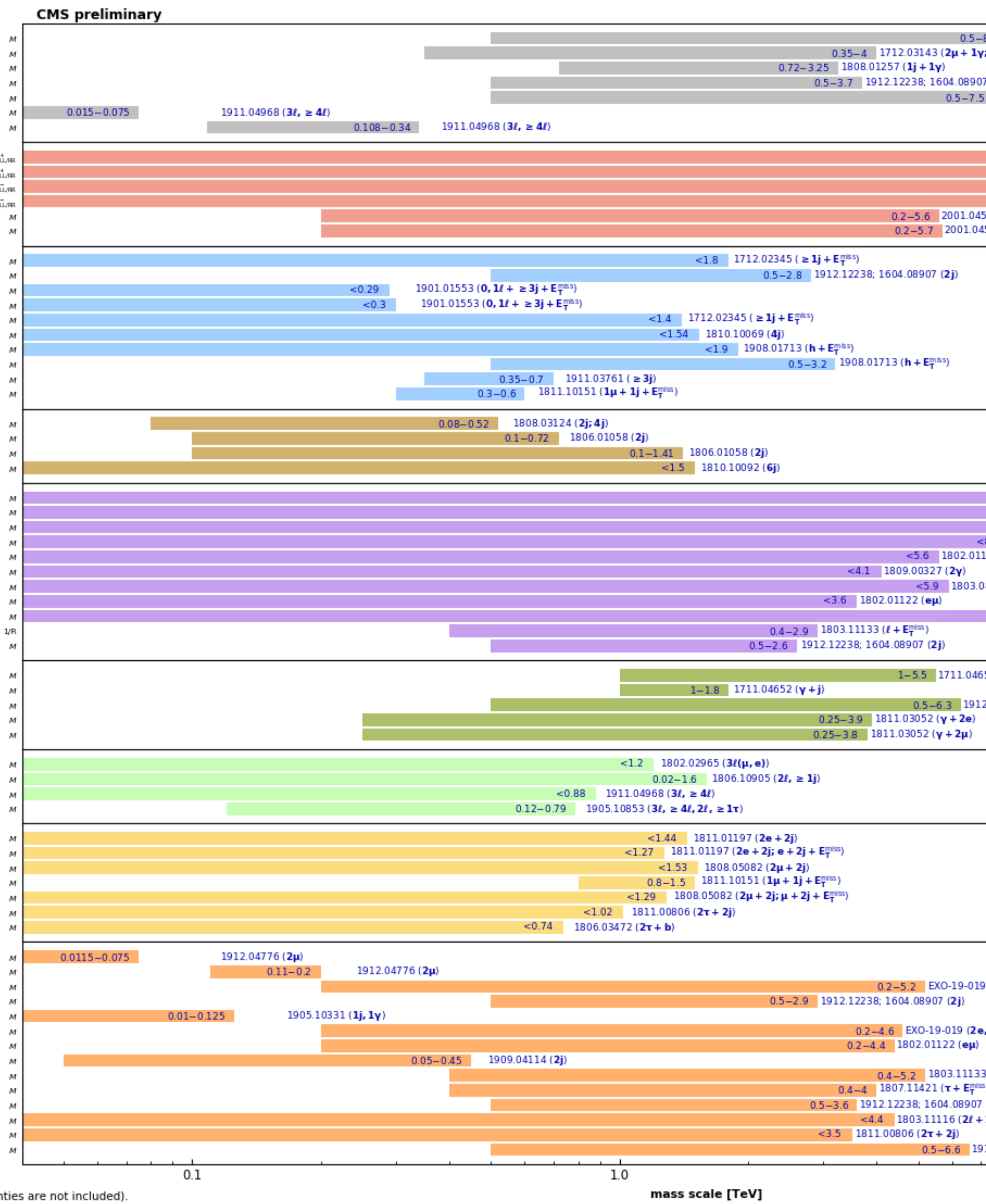
ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Overview of CMS EXO results

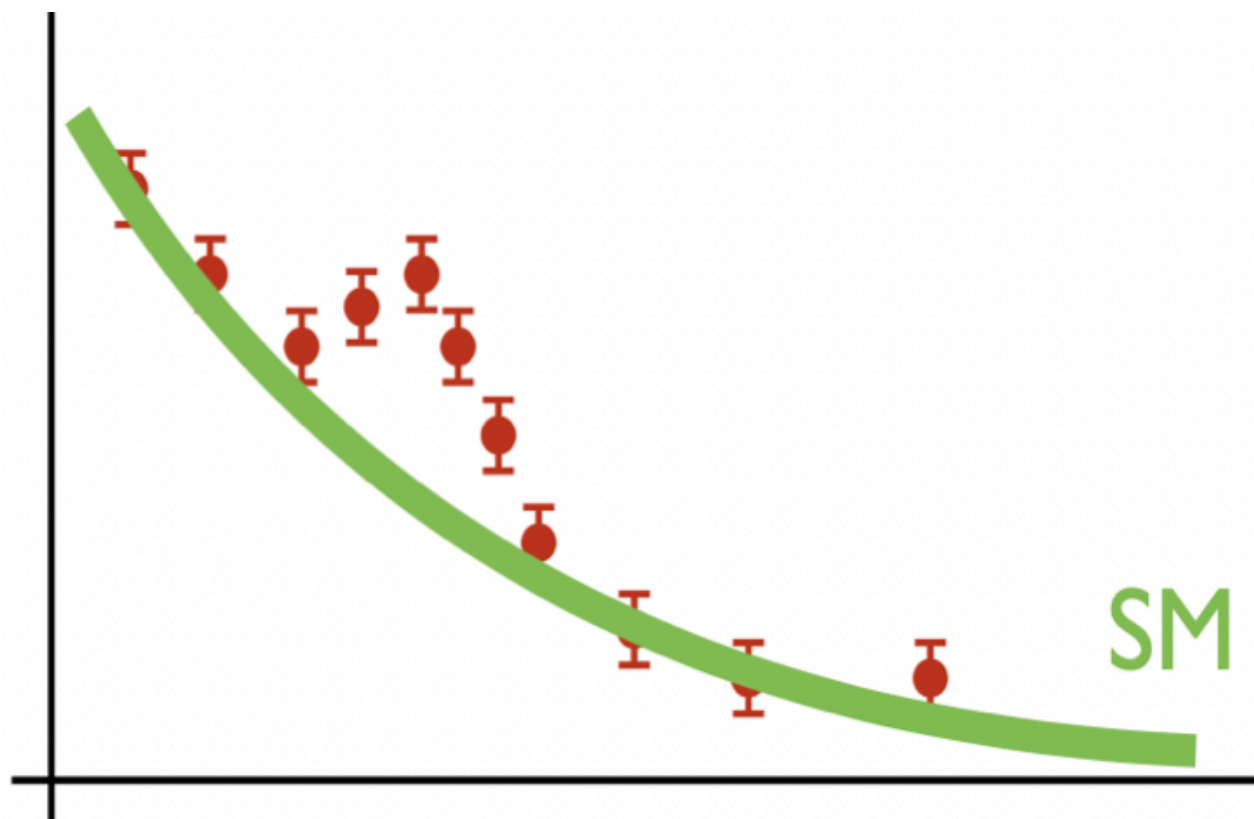


New physics without new particle

New physics beyond the LHC threshold: paradigm shift for BSM searches

Or sub-GeV light new physics

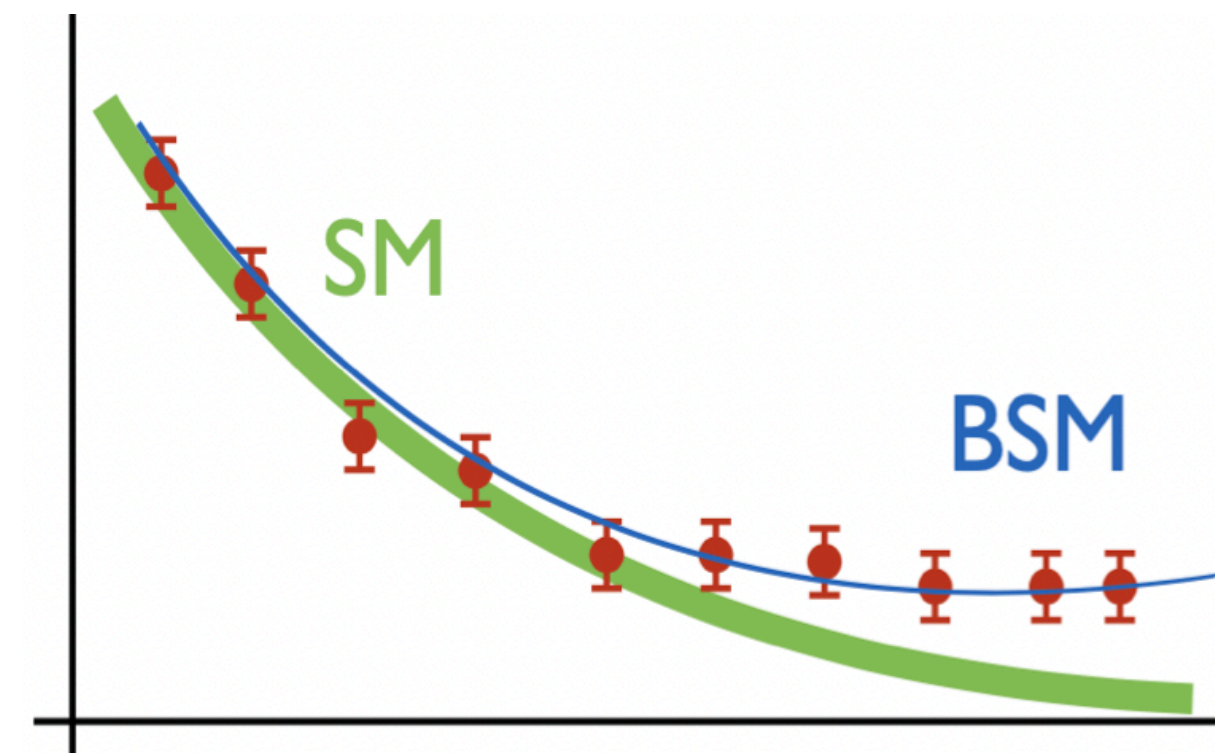
Resonance Searches



Experiments: Resonance bump hunting at the LHC

Theories: New physics model building

Deviation Searches



Experiments: deviation from SM at the LHC

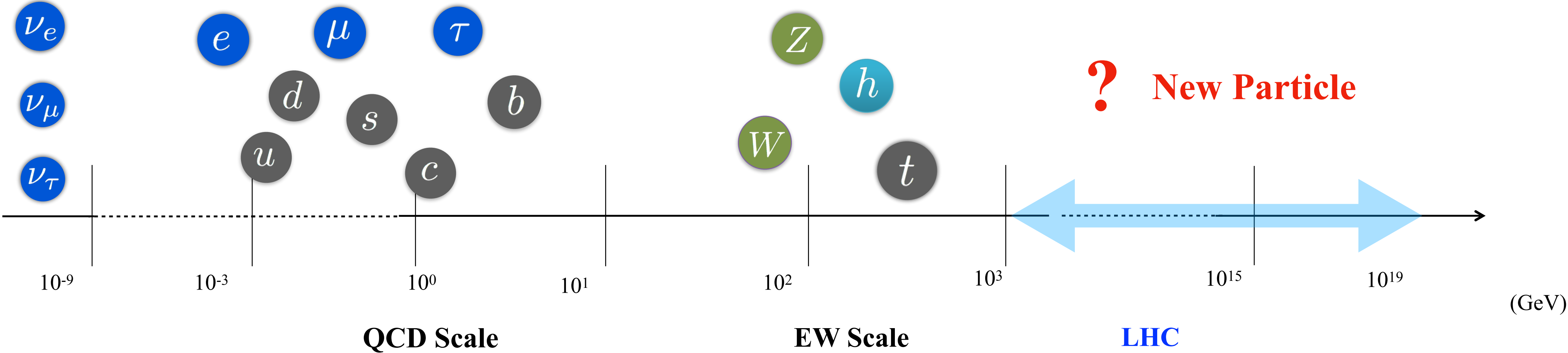
Theories: Effective field theory (EFT) description

New Physics without new particles

Effective Field Theory Description

Using neutrino as example

From thousand models to a unique theory

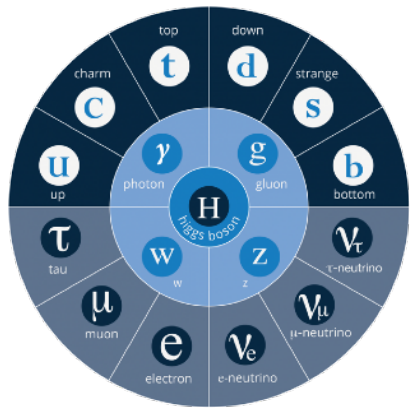


Bottom-up EFT theory

Top-down model building

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

A unique SMEFT theory



+ new particle + new symmetry

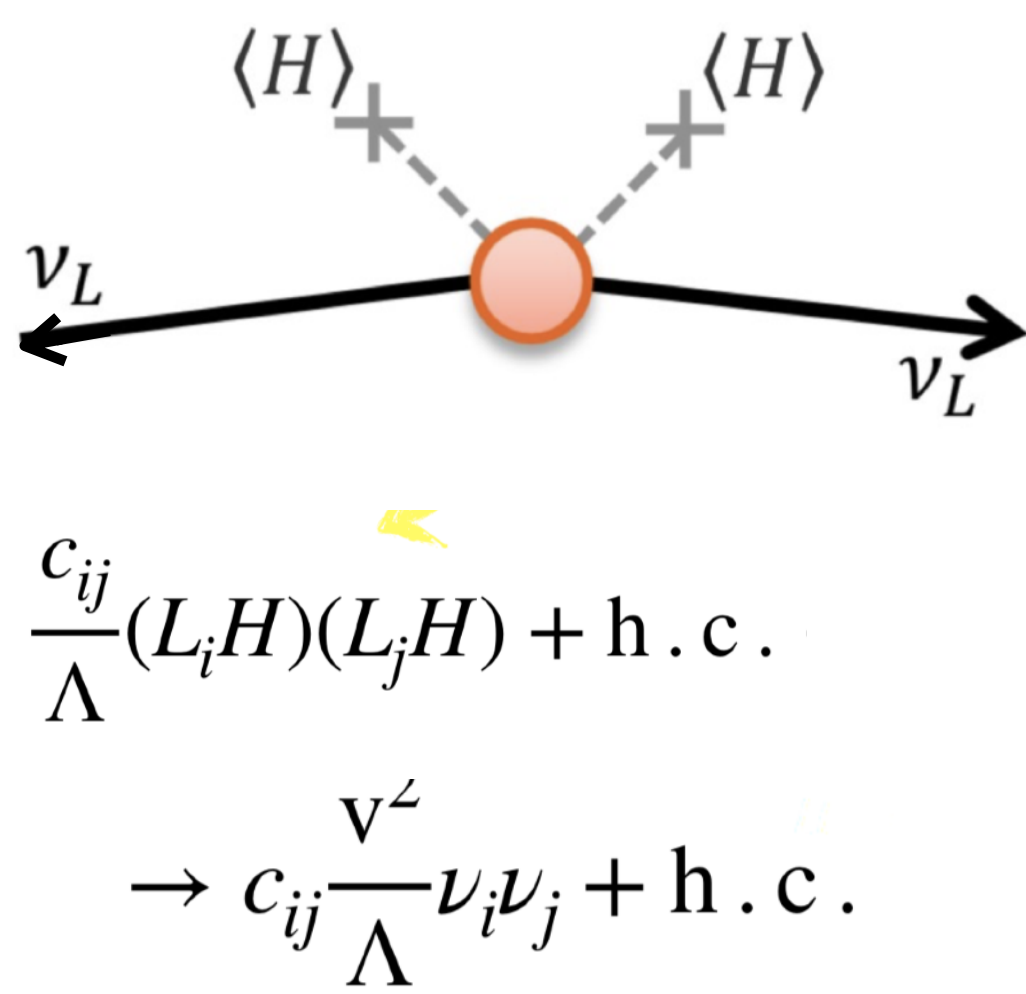
Thousands of models

Standard model effective field theory

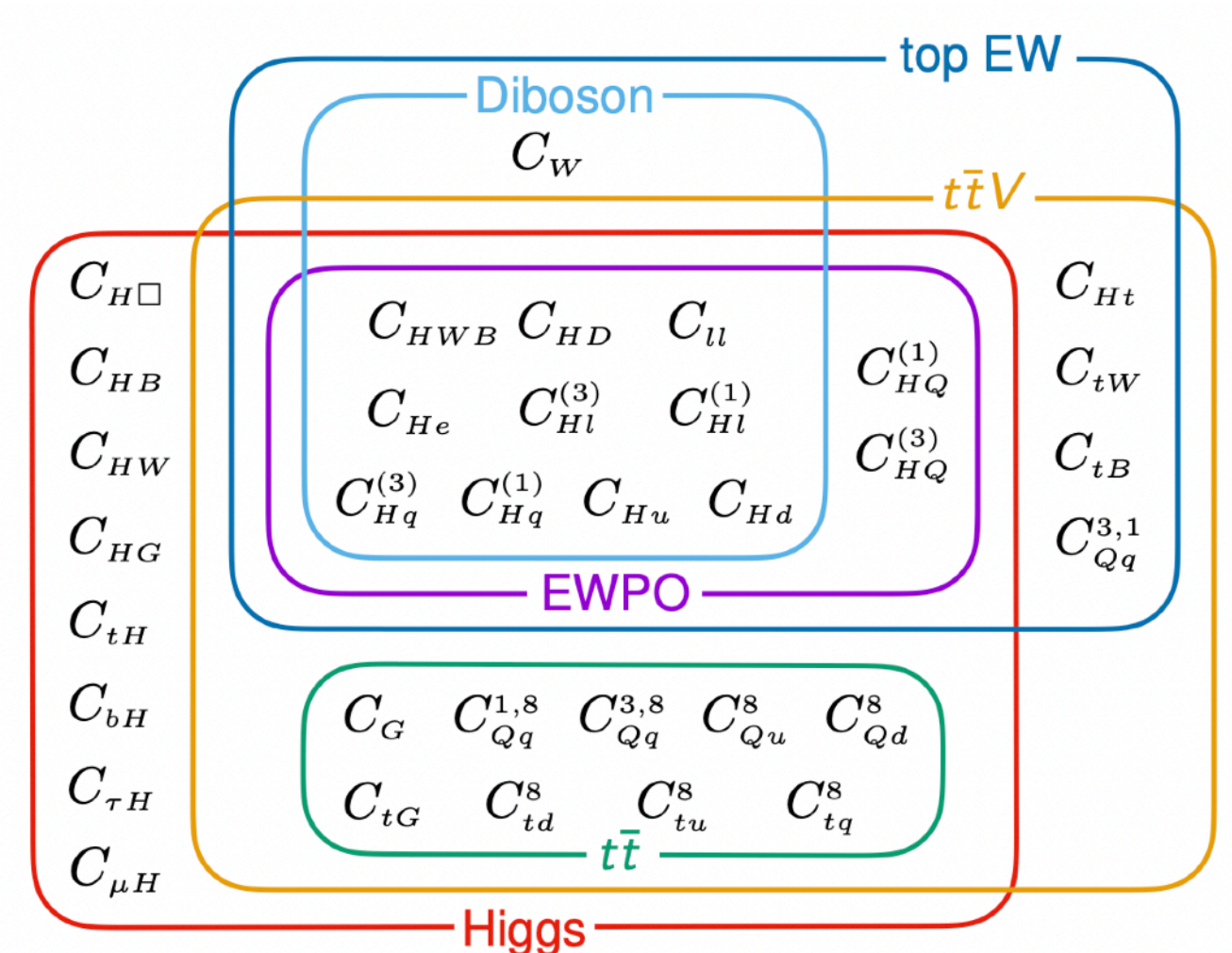
Based on SM particles and SM symmetry (no new particle/symmetry), write the most general Lagrangian

$$\mathcal{L}_{\text{EFT}} = \underbrace{\mathcal{L}_{\mathcal{D} \leq 4}}_{\text{Standard Model}} + \underbrace{\frac{\mathcal{L}_5}{\Lambda}}_{\text{Weinberg Operator}} + \underbrace{\frac{\mathcal{L}_6}{\Lambda^2}}_{\text{Dim-6 84}} + \underbrace{\frac{\mathcal{L}_7}{\Lambda^3}}_{30} + \underbrace{\frac{\mathcal{L}_8}{\Lambda^4}}_{993} + \underbrace{\frac{\mathcal{L}_9}{\Lambda^5}}_{560} + \dots$$

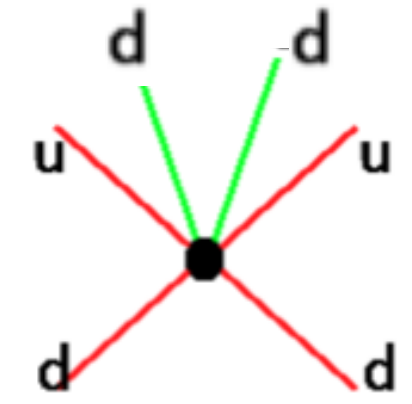
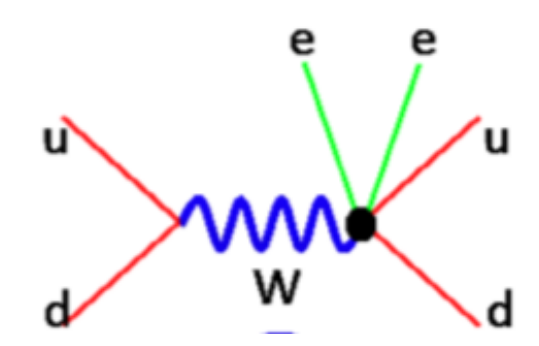
Dim-5: Weinberg operator



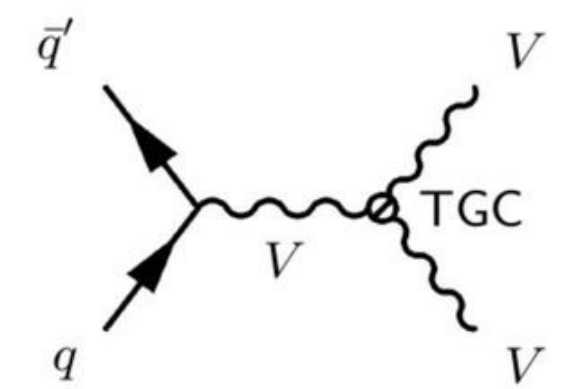
Dim-6: typical process



Dim-7,9: BNV, LNV



Dim-8: nTGC, VVV

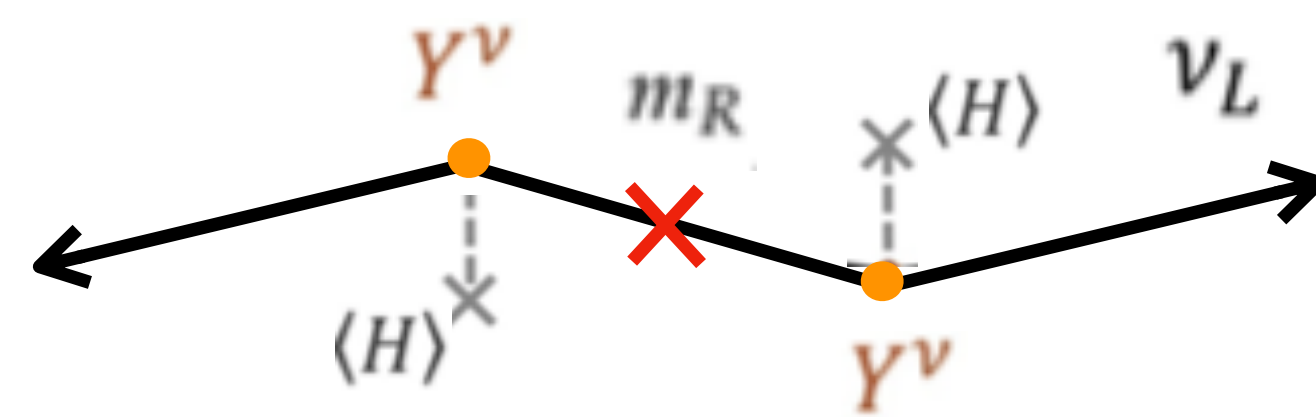


SMEFT provides systematic parameterization of all possible Lorentz-inv. new physics

Dim-5 Weinberg operator

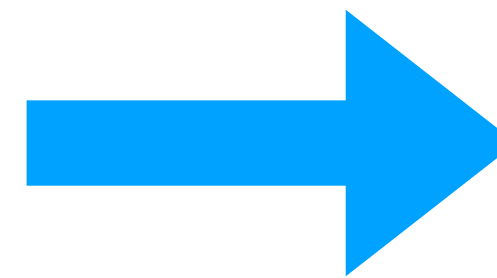
The neutrino masses from Weinberg operator is the first example of new physics without new particle

Beyond the current experimental searches

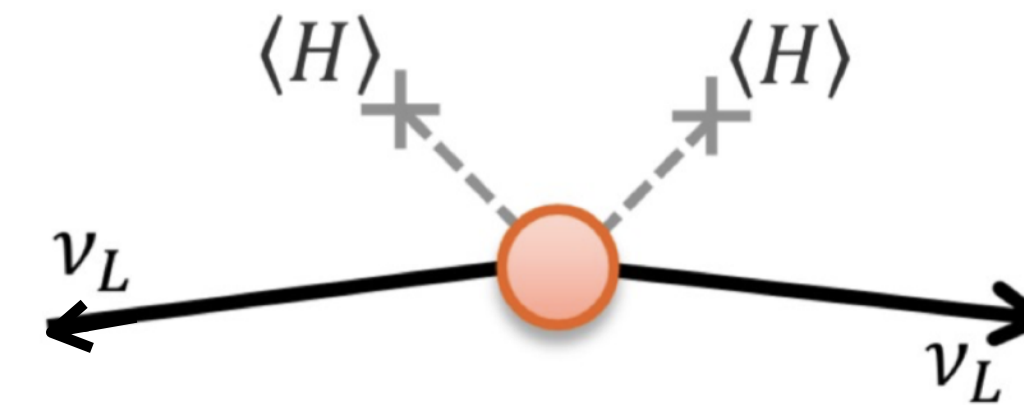


for Majorana neutrino

$$m_\nu = \frac{(Y^\nu v_{EW})^2}{m_R}$$



Measurements of neutrino oscillation



$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \text{h.c.}$$

$$\rightarrow c_{ij} \frac{v^2}{\Lambda} \nu_i \nu_j + \text{h.c.}$$

[Weinberg, 1979]

“... the effective field theory point of view had predicted the neutrino masses”

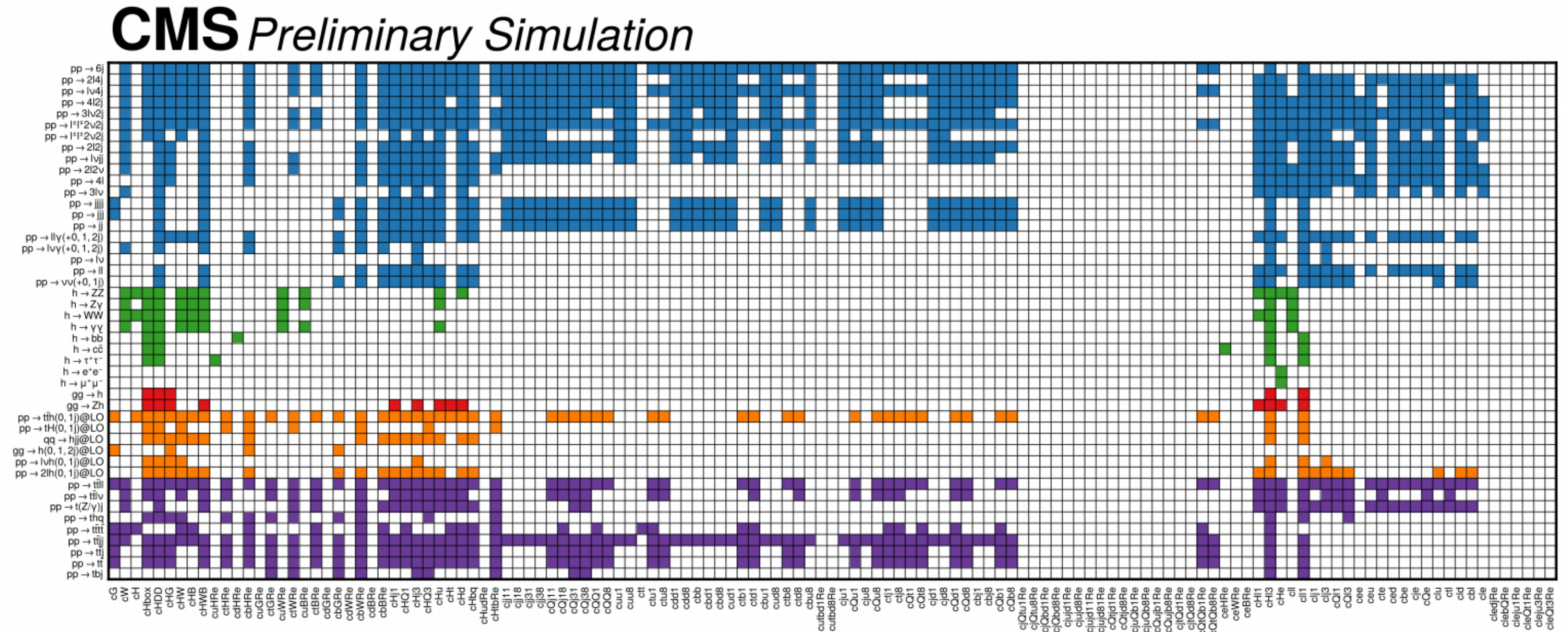
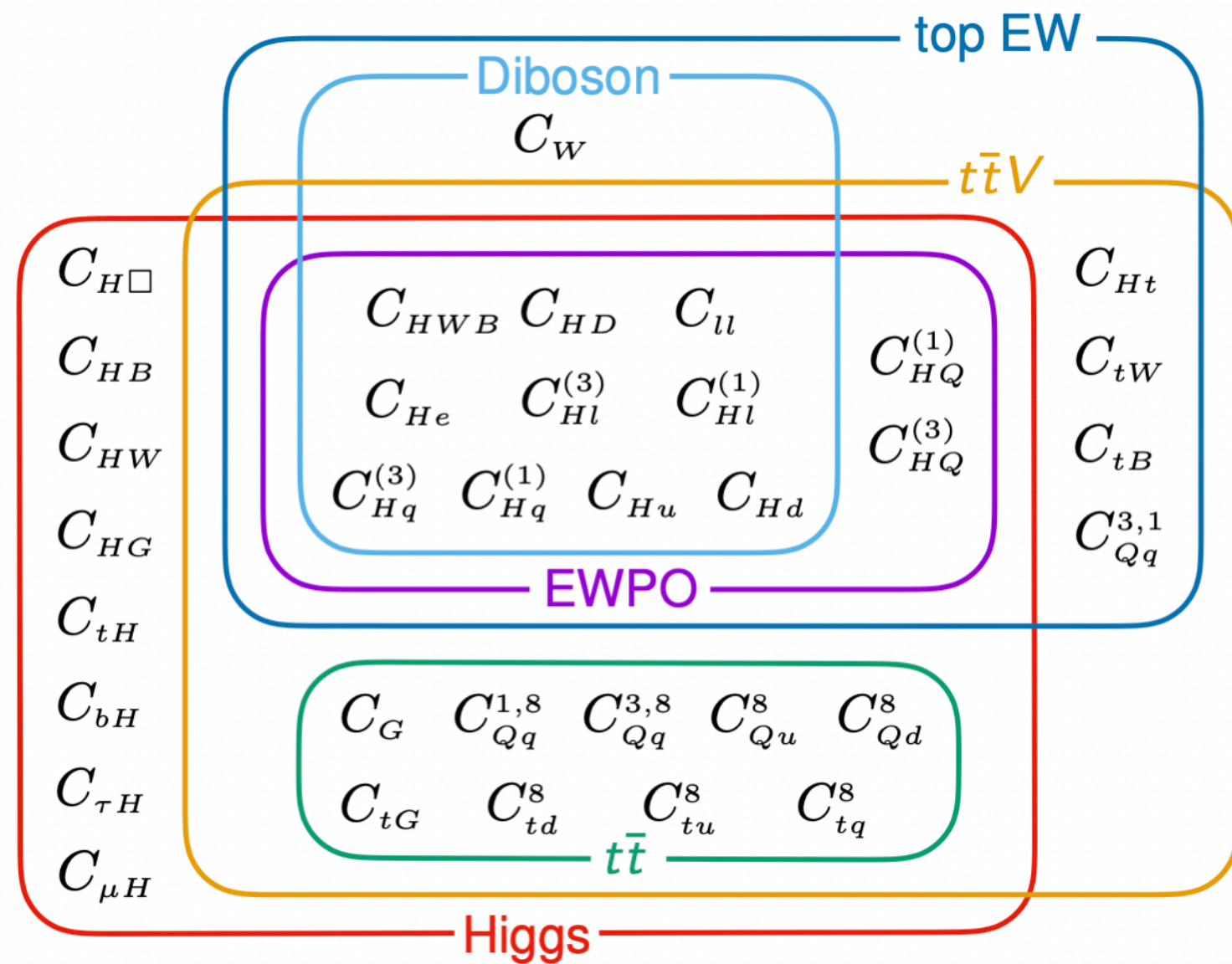


[Weinberg, 2021]

Dim-6 operators

Dimension-6 operators parametrize new physics effects at low energy, electroweak precision, diboson, top and Higgs boson physics, etc

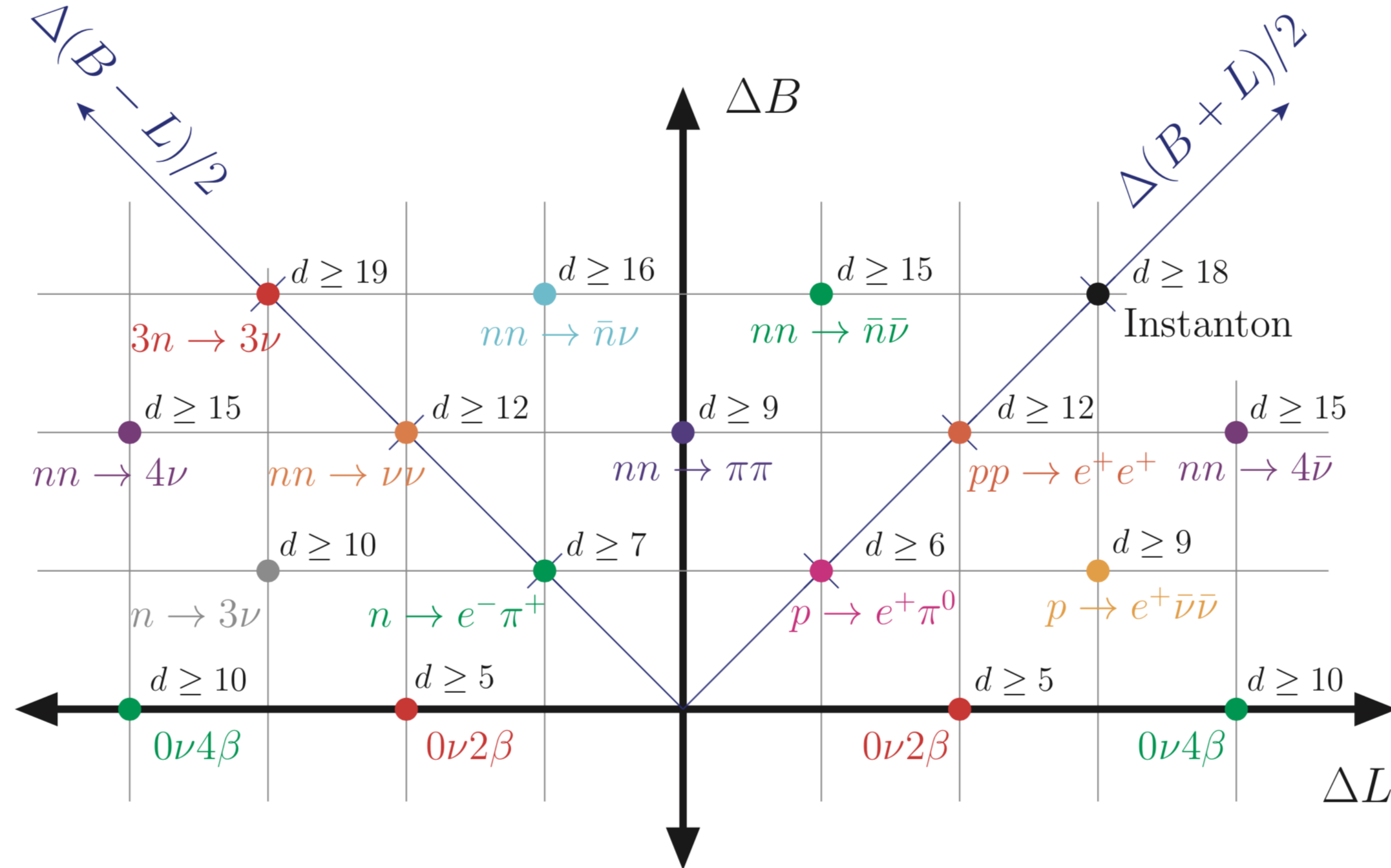
One important task of LHC run-3 : dim-6 operator Wilson coefficients



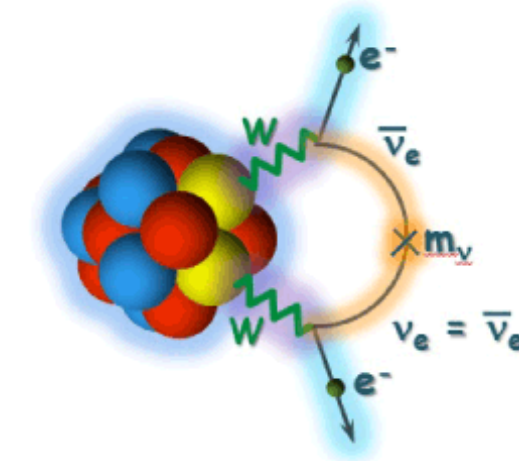
[Ellis, Madigan, Mimasu, Sanz, You 2021]

Dim-7 and higher

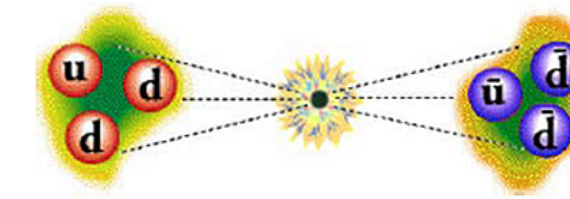
Matter-antimatter asymmetry: baryon number violation and lepton number violation



[Heeck, Takhistov, 2020]



0νbb, di-nucleon decay

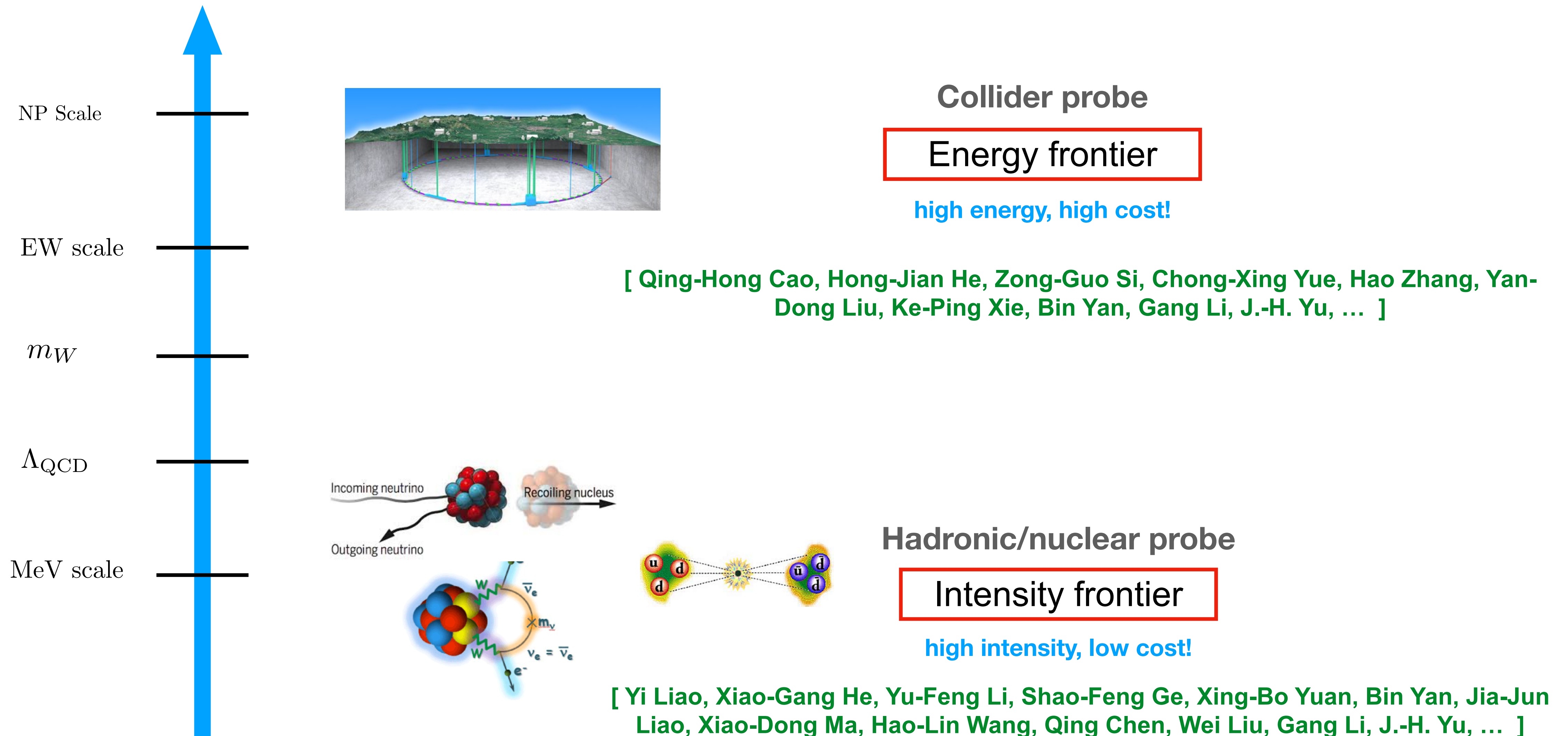


**Neutron-antineutron
Oscillation at dim-9**

[Ramsey-Musolf, Yi Liao, Xiao-Gang He, Shao-Long Chen, Xiao-Dong Ma, Hao-Lin Wang, Gang Li, J.-H. Yu, ...]

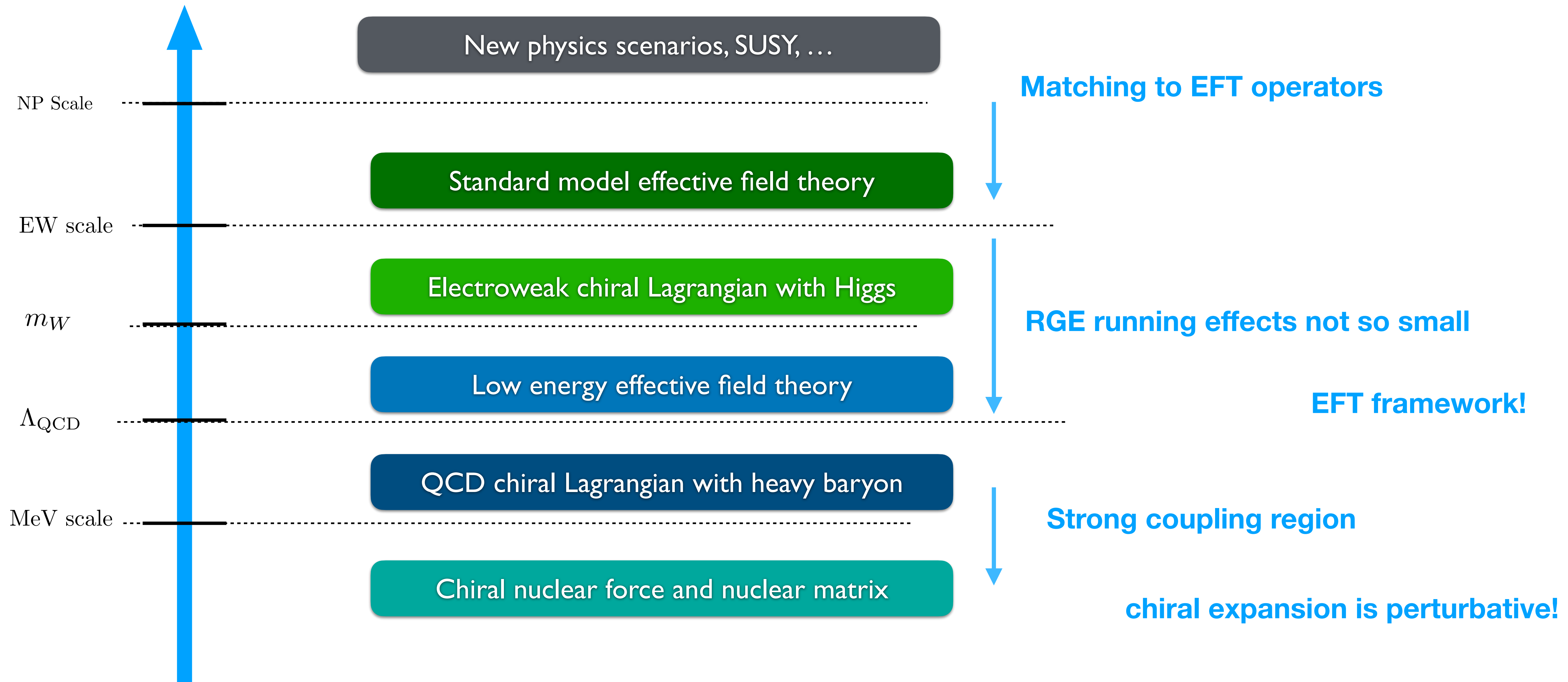
Complementary search at high and low energies

Interplay between high energy process and low energy process



Tower of EFTs

EFT provides the systematic framework to resum large log from huge scale differences



Operator bases and RGEs

Easy to write EFT operators, but hard to reduce to complete/non-redundant basis

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

Standard
Model

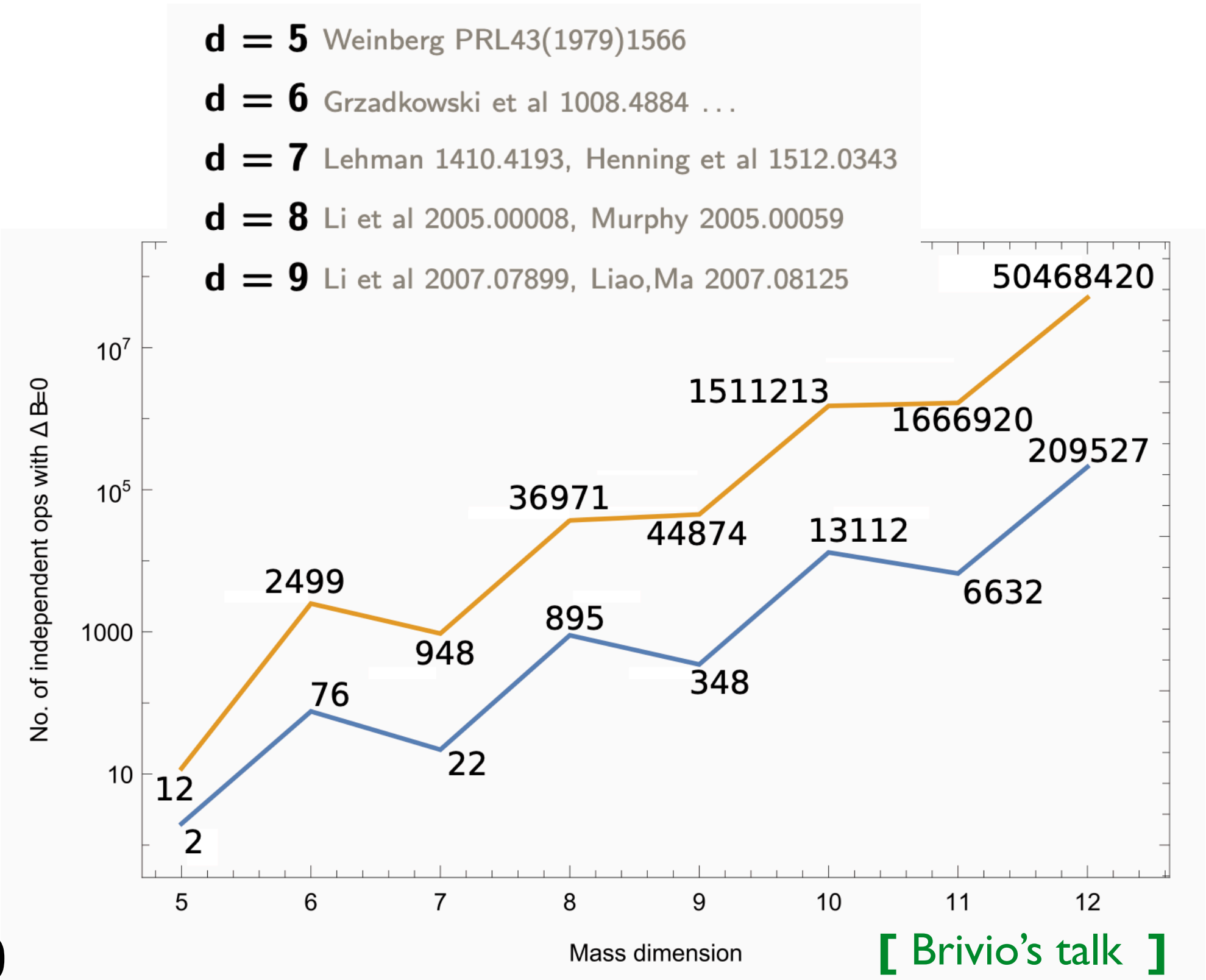
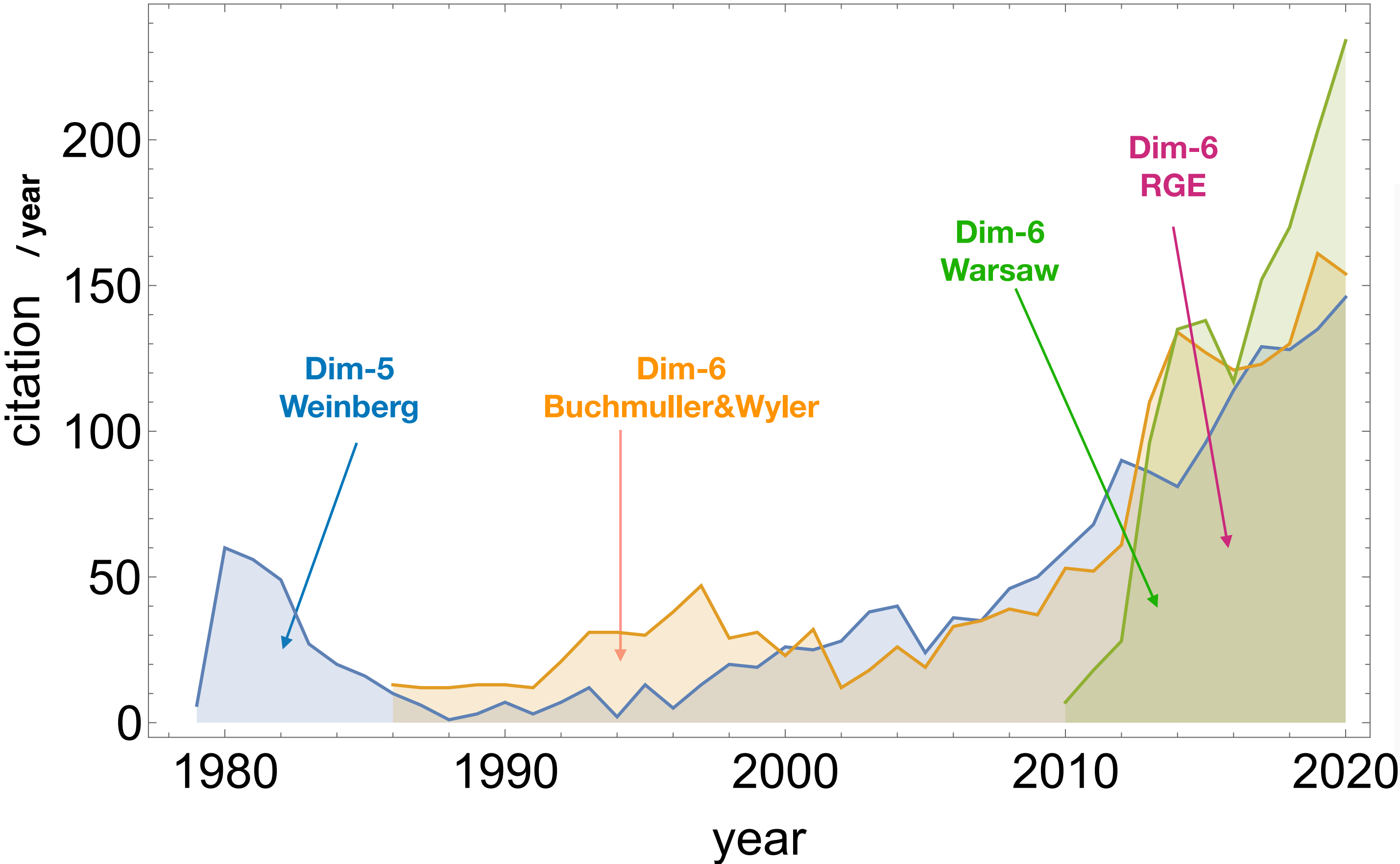
Weinberg
Operator

Dim-6
84

30

993

560



EFT operator from amplitude

Scattering amplitude based on on-shell **particle**

$$\mathcal{S} = \text{---} \bullet \text{---} + \text{---} \bullet \text{---} + \text{---} \bullet \text{---} + \text{---} \bullet \text{---} + \text{---} \bullet \text{---} + \dots$$

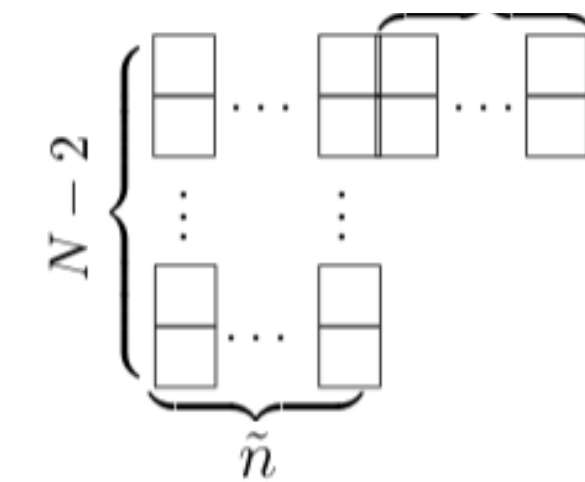
Classified by external particles

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639]



SL(2, C) x U(N) symmetry

$$\lambda_i \rightarrow \sum_j U_i^j \lambda_j, \quad \tilde{\lambda}^i \rightarrow \sum_k U^{\dagger i}_k \tilde{\lambda}^k$$



[Also Henning, Melia, Shadmi, Jing Shu, Teng Ma, ...]

Lagrangian based on local **field**

Expansion by mass dimension

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

Standard
Model

Weinberg
Operator

84

30

993

560

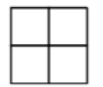
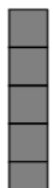
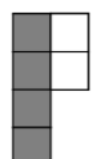
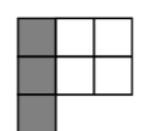
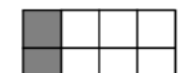
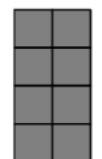
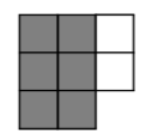
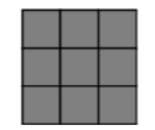
Operator and RG running

SMEFT on-shell basis is obtained and RGE is calculated using unitarity cut method

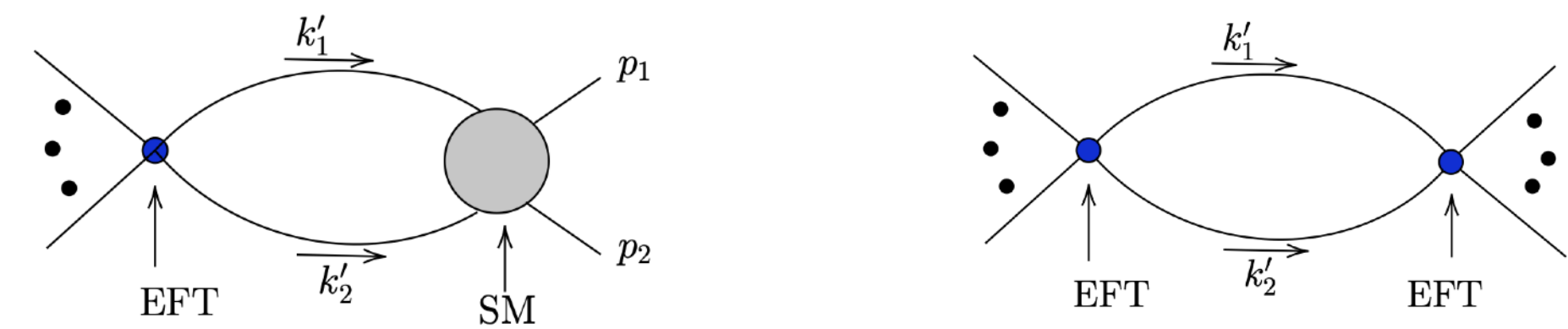
Dim-8: 993 operators from 16 Young diagrams

[Hao-Lin Li, Jing Shu, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2005.00008]

$\begin{smallmatrix} n \\ \bar{n} \end{smallmatrix}$	0	1	2	3	4
0	ϕ^8	$\psi^2\phi^5$	$\psi^4\phi^2, F_L\psi^2\phi^3, F_L^2\phi^4$	$F_L\psi^4, F_L^2\psi^2\phi, F_L^3\phi^2$	F_L^4
1	$\psi^{\dagger 2}\phi^5$	$\psi^{\dagger 2}\psi^2\phi^2, \psi^{\dagger}\psi\phi^4D, \phi^6D^2$	$F_L\psi^{\dagger 2}\psi^2, F_L^2\psi^{\dagger 2}\phi, \psi^{\dagger}\psi^3\phi D, F_L\psi^{\dagger}\psi\phi^2D, \psi^2\phi^3D^2, F_L\phi^4D^2$	$F_L^2\psi^{\dagger}\psi D, \psi^4D^2, F_L\psi^2\phi D^2, F_L^2\phi^2D^2$	
2	$\psi^{\dagger 4}\phi^2, F_R\psi^{\dagger 2}\phi^3, F_R^2\phi^4$	$F_R\psi^{\dagger 2}\psi^2, F_R^2\psi^2\phi, \psi^{\dagger 3}\psi\phi D, F_R\psi^{\dagger}\psi\phi^2D, \psi^{\dagger 2}\phi^3D^2, F_R\phi^4D^2$	$F_R^2F_L^2, F_RF_L\psi^{\dagger}\psi D, \psi^{\dagger 2}\psi^2D^2, F_R\psi^2\phi D^2, F_L\psi^{\dagger 2}\phi D^2, F_RF_L\phi^2D^2, \phi^4D^4, \psi^{\dagger}\psi\phi^2D^3$		
3	$F_R\psi^{\dagger 4}, F_R^2\psi^{\dagger 2}\phi, F_R^3\phi^2$	$F_R^2\psi^{\dagger}\psi D, \psi^{\dagger 4}D^2, F_R\psi^{\dagger 2}\phi D^2, F_R^2\phi^2D^2$			
4	F_R^4				

$\begin{smallmatrix} n \\ \tilde{n} \end{smallmatrix}$	0	1	2	3	4
0					
1					
2					
3					
4					

[Chao Wu, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2512.21724]



$$\mu \frac{d}{d\mu} C_j = \gamma_{ji} C_i$$

[Also Jing Shu, Teng Ma, Y.H. Zheng]

$$\gamma_{ji}^{\text{UV}} C_i^f \mathcal{O}_j^f = \frac{1}{8\pi^2} \sum_{\mathcal{I}} b_{\mathcal{I}}.$$

$$b_I = \frac{2}{\pi} \int d\Phi \mathcal{A}_L \mathcal{A}_R$$

SMEFT and LEFT operator bases

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda^2} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

Standard Model Effective Field Theory

Low Energy Effective Field Theory

SU(3) x SU(2) x U(1) gauge symmetry

SU(3) x U(1) gauge symmetry

Dim-5	[Weinberg, 1979]
Dim-6	[Buchmuller,Wyler, 1986] [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]
Dim-7	[Lehman, 2014] [Henning, Lu, Melia, Murayama, 2015] [Liao, Ma, 2016]
Dim-8	[Li, Ren, Shu, Xiao, Yu , Zheng, 2020] [Murphy, 2020]
Dim-9	[Li, Ren, Xiao, Yu , Zheng, 2020] [Liao, Ma, 2020]

Dim-5	[Dirac, 1932]
Dim-6	[Fermi, 1934] [Lee,Yang, 1956] [Jenkins, Manohar, Stoffer, 2017]
Dim-7	[Liao, Ma, Wang, 2020] [Li, Ren, Xiao, Yu , Zheng, 2020]
Dim-8	[Li, Ren, Xiao, Yu , Zheng, 2020] [Murphy, 2020]
Dim-9	[Li, Ren, Xiao, Yu , Zheng, 2020]

Chiral Lagrangian for QCD and electroweak

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{p^2} + \mathcal{L}_{p^3} + \mathcal{L}_{p^4} + \mathcal{L}_{p^5} + \mathcal{L}_{p^6} + \dots$$

Goldstone shift symmetry imposed

ChPT and Chiral EFT

EW Chiral Lagrangian = HEFT

LO Lagrangian

[Weinberg, 1979]

Pure mesonic

[Gasser, Leutwyler, 1984, 1985]

[Fearing, Scherer 1994]

[Bijnsens, Colangelo, Ecker, 1999]

[Jiang, Ge, Wang, 2014]

[Bijnsens, Hermansson, Wang, 2018]

[Li, Sun, Tang, **J.H.Yu**, 2404.14152]

nucleon-meson

[Krause, 1990]

[Ecker, 1994]

[Fettes, Meisner, Mojzis, Steininger, 2000]

[Oller, Verbeni, Prades, 2006]

[Frink, Meisner, 2006]

[Jiang, Chen, Liu, 2017]

[Song, Sun, **J.H.Yu**, 2404.15047]

nucleon-nucleon

[Weinberg 1990]

[van Kolck, Ordóñez, 1992]

[Petschauer, Kaiser, 2013]

[Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2020]

LO Lagrangian

[Weinberg, 1979]

NLO bosonic

[Appelquist, Bernard, 1980]

[Longhitano, 1980, 1981]

[Feruglio, 1993]

NLO 2-fermion

[Buchalla, Cata, Krause, 2014]

NLO 4-fermion

[Buchalla, Cata, Krause, 2014]

[Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018]

[Sun, Xiao, **Yu**, 2206.07722]

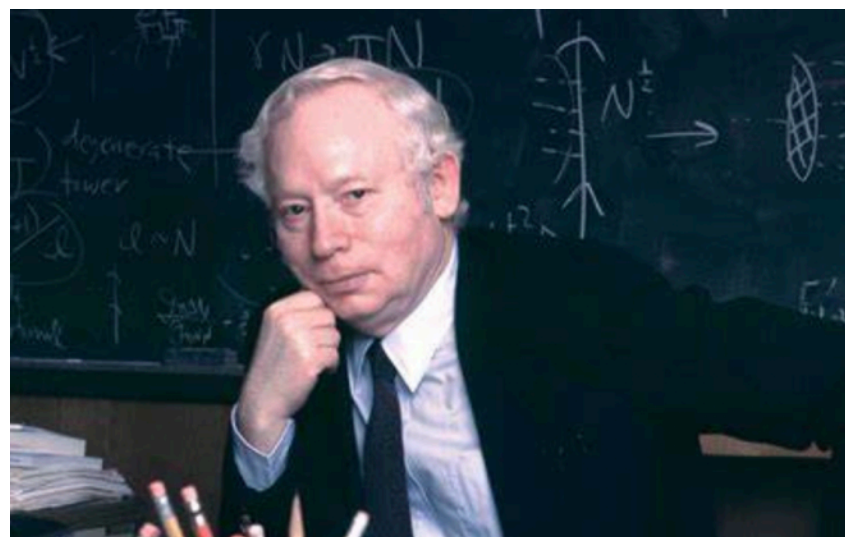
$$\begin{aligned} \mathcal{O}_{33}^{Lh\psi^4} &= (\bar{q}_{Ls} \gamma_\mu \tau^I \mathbf{T} q_{Lp}) (\bar{q}_{Rr} \gamma^\mu \mathbf{U}^\dagger \tau^I \mathbf{U} q_{Rt}) \mathcal{F}_{33}^{Lh\psi^4}(h), \\ \mathcal{O}_{34}^{Lh\psi^4} &= (\bar{q}_{Ls} \gamma_\mu \lambda^A \tau^I \mathbf{T} q_{Lp}) (\bar{q}_{Rr} \gamma^\mu \lambda^A \mathbf{U}^\dagger \tau^I \mathbf{U} q_{Rt}) \mathcal{F}_{34}^{Lh\psi^4}(h), \\ \mathcal{O}_{89}^{Lh\psi^4} &= (\bar{l}_{Ls} \gamma_\mu \tau^I l_{Lp}) (\bar{l}_{Rt} \sigma^{\mu\nu} \tau^I \mathbf{U}^\dagger \mathbf{T} \mathbf{U} l_{Rr}) \mathcal{F}_{89}^{Lh\psi^4}(h), \\ \mathcal{O}_{107}^{Lh\psi^4} &= (\bar{l}_{Ls} \gamma_\mu \tau^I \mathbf{T} l_{Lp}) (\bar{q}_{Lr} \gamma^\mu \tau^I q_{Lr}) \mathcal{F}_{107}^{Lh\psi^4}(h), \\ \mathcal{O}_{113}^{Lh\psi^4} &= (\bar{q}_{Ls} \gamma_\mu \tau^I \mathbf{T} q_{Lp}) (\bar{q}_{Lr} \gamma^\mu \tau^I q_{Lr}) \mathcal{F}_{113}^{Lh\psi^4}(h), \\ \mathcal{O}_{119}^{Lh\psi^4} &= (\bar{q}_{Ls} \gamma_\mu \mathbf{U}^\dagger \tau^I \mathbf{U} q_{Lp}) (\bar{q}_{Lr} \gamma^\mu \tau^I q_{Lr}) \mathcal{F}_{119}^{Lh\psi^4}(h), \\ \mathcal{O}_{125}^{Lh\psi^4} &= (\bar{l}_{Ls} \gamma_\mu \tau^I \mathbf{T} l_{Lp}) (\bar{q}_{Rt} \gamma^\mu \mathbf{U}^\dagger \tau^I \mathbf{U} q_{Rr}) \mathcal{F}_{125}^{Lh\psi^4}(h), \\ \mathcal{O}_{140}^{Lh\psi^4} &= \mathcal{Y} \left[\prod_{a,b,c} \epsilon^{abc} e^{in} e^{km} ((\mathbf{T} l_L^T)_{pm} C(\mathbf{T} q_L)_{ran}) (q_{Lra} C q_{Lta}) \right] \mathcal{F}_{140}^{Lh\psi^4}(h), \\ \mathcal{O}_{160}^{Lh\psi^4} &= \mathcal{Y} \left[\prod_{a,b,c} \epsilon^{abc} e^{in} e^{km} ((\mathbf{T} l_R^T)_{pm} C(\mathbf{T} q_R)_{ran}) (q_{Rsa} C q_{Rta}) \right] \mathcal{F}_{160}^{Lh\psi^4}(h). \end{aligned}$$

NNLO Basis

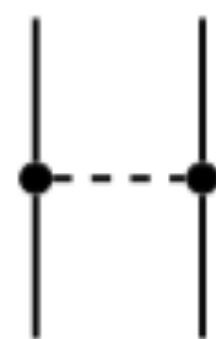
[Sun, Xiao, **Yu**, 2210.14939]

High precision nuclear force

Chiral Lagrangian can be extended to describe nuclear force from first principles



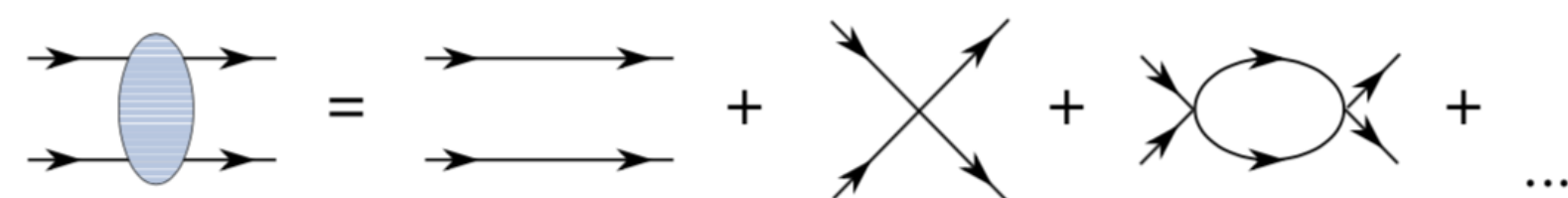
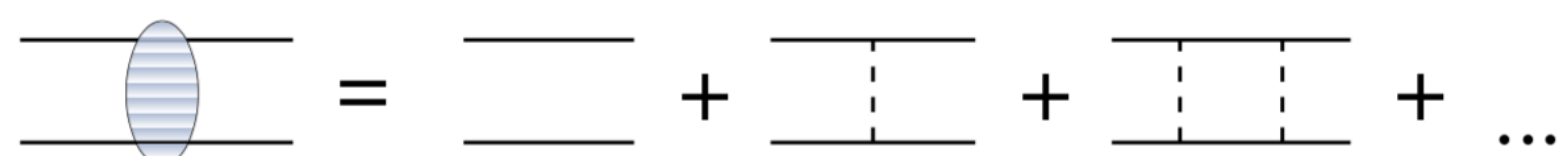
Pion exchange



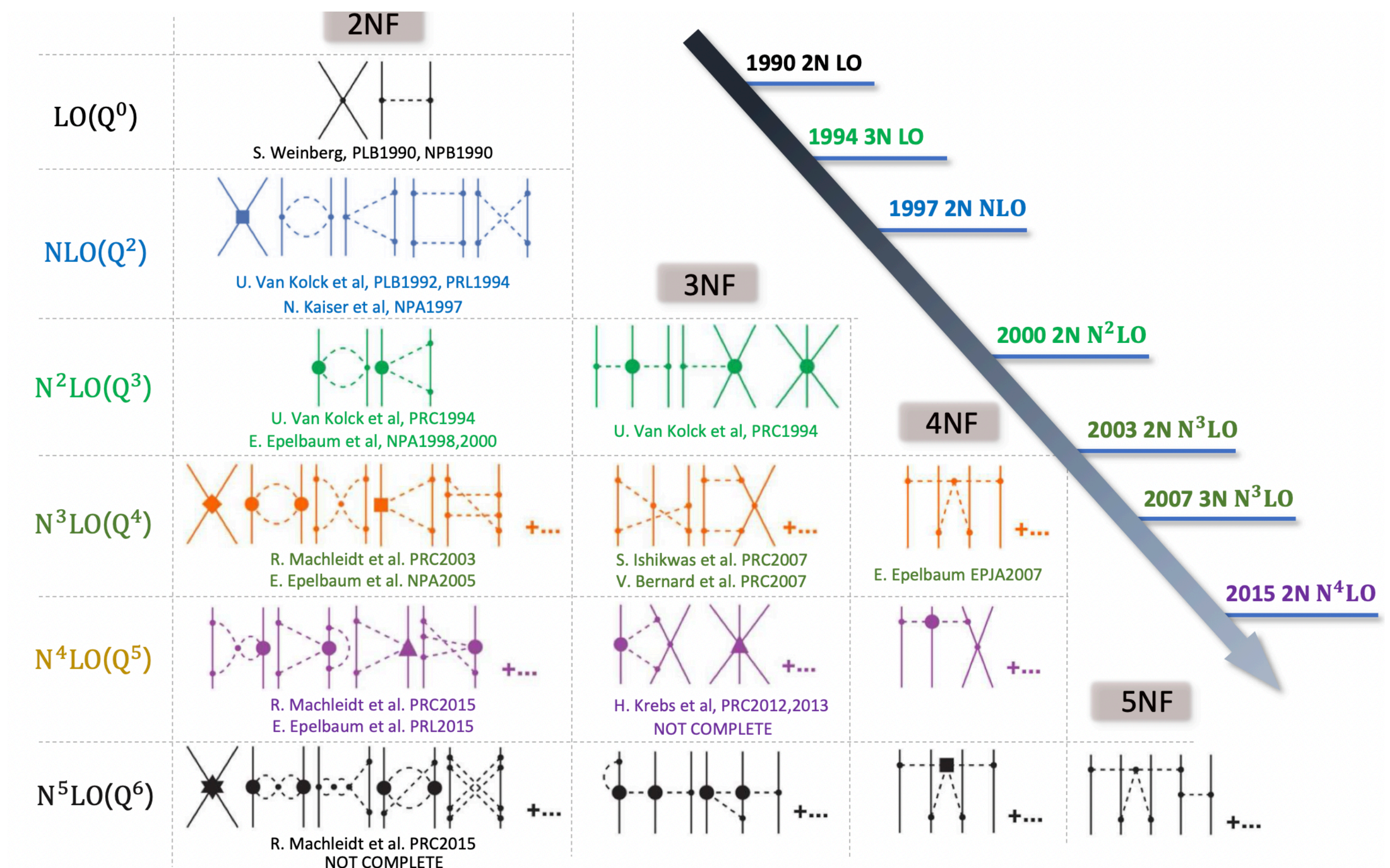
N-N hard core



Nuclear potential from resumming IR div diagrams



Breakdown in perturbation theory = nuclear bound states



Weinberg scheme

[Entem, Machleidt, Nosyk, 2020]

NN and 3N Operators

Operator basis for non-relativistic field with SO(3) symmetry

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{NN} + \mathcal{L}_{DNN} + \mathcal{L}_{D^2NN} + \mathcal{L}_{NNN} + \mathcal{L}_{DNNN} + \mathcal{L}_{D^2NNN} + \cdots$$

Nucleon-nucleon Operators

3N Operators

LO

[Weinberg 1990] [Weinberg 1991]

[Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2016]

[van Kolck, Ordonez, 1992]

NLO

[Girlanda, Pastore, Schiavilla, Viviani, 2010]

[Nasoni, Filandri, Girlanda, 2023]

[Petschauer, Kaiser, 2013] [Xiao, Geng, Ren, 2019]

NNLO

[Sun, Wang, **Yu**, 2024]

[Sun, Wang, **Yu**, 2024]

[Li, Wang, **Yu**, 2025]

[Li, Wang, **Yu**, 2025]

Then imposing non-linearized Lorentz symmetry from coset structure

$$\Psi(x) = e^{-imv \cdot x} \left[\underbrace{e^{imv \cdot x} P_v^+ \Psi(x)}_{\equiv \mathcal{N}_v(x)} + \underbrace{e^{imv \cdot x} P_v^- \Psi(x)}_{\equiv \mathcal{H}_v(x)} \right]$$

Relate to relativistic NN and 3N operators

General Lagrangian Construction

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639]

Amplitude Basis Construction for Effective Field Theory

ABC4EFT package

- Home
- Repo
- Downloads
- Contact

Welcome to the HEPForge Project: ABC4EFT

This is the website for the Mathematica package: Amplitude Basis Construction for Effective Field Theories (ABC4EFT).

Package

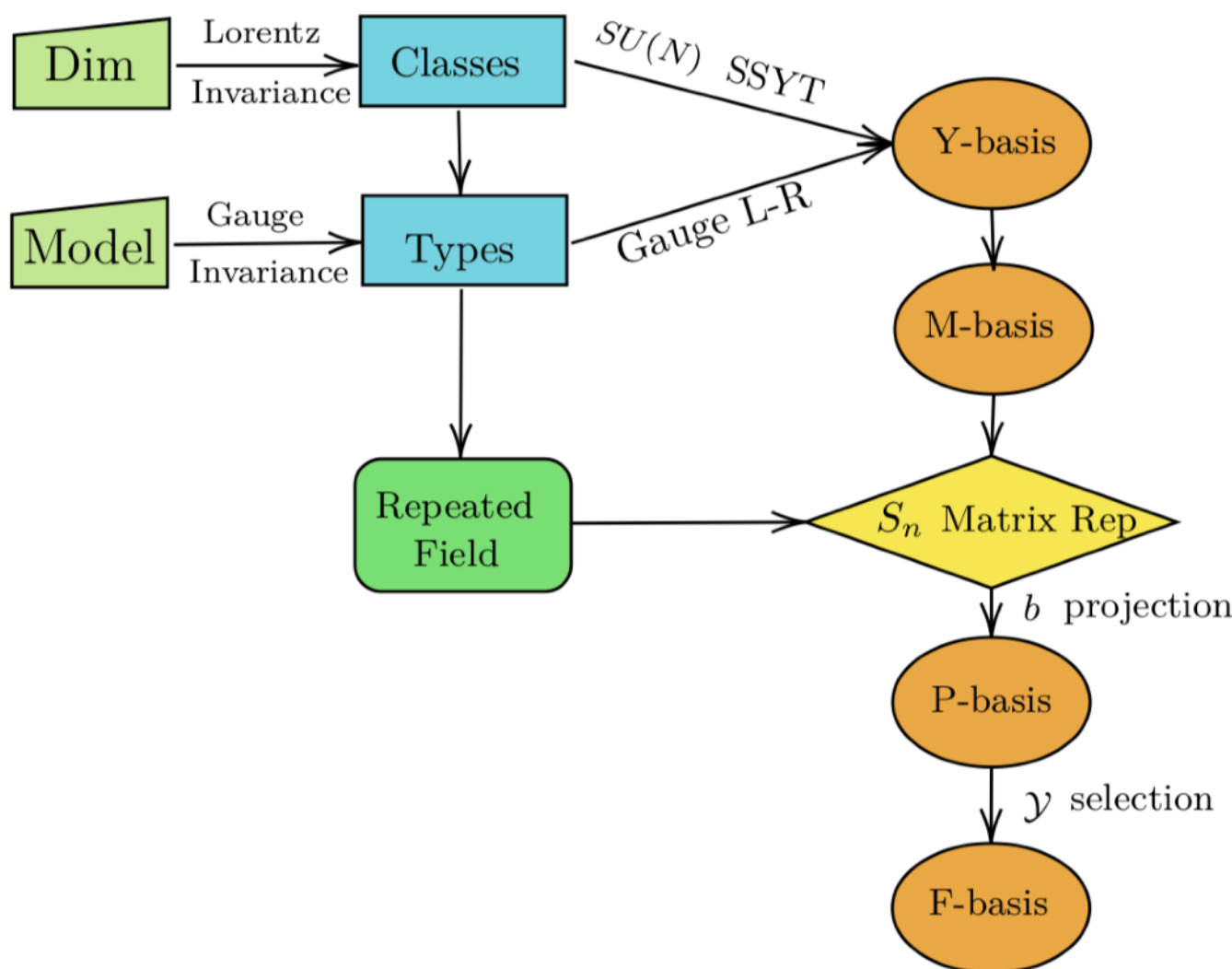
This package has the following features:

- It provides a general procedure to construct the independent and complete operator bases for generic Lorentz invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dimension.
- Various operator bases have been systematically constructed to emphasize different aspects: operator independence (y-basis), flavor relation (p-basis) and conserved quantum number (j-basis).
- It provides a systematic way to convert any operator into our on-shell amplitude basis and the basis conversion can be easily done.

Authors

The collaboration group at Institute of Theoretical Physics, CAS Beijing (ITP-CAS)

- Hao-Lin Li (previously postdoc at ITP-CAS, now postdoc at UC Louvain)
- Zhe Ren (4th-year graduate student at ITP-CAS)
- Ming-Lei Xiao (previously postdoc at ITP-CAS, now postdoc at Northwestern and Argonne)
- **Jiang-Hao Yu** (professor at ITP-CAS)
- Yu-Hui Zheng (5th-year graduate student at ITP-CAS)



Fully Automatic

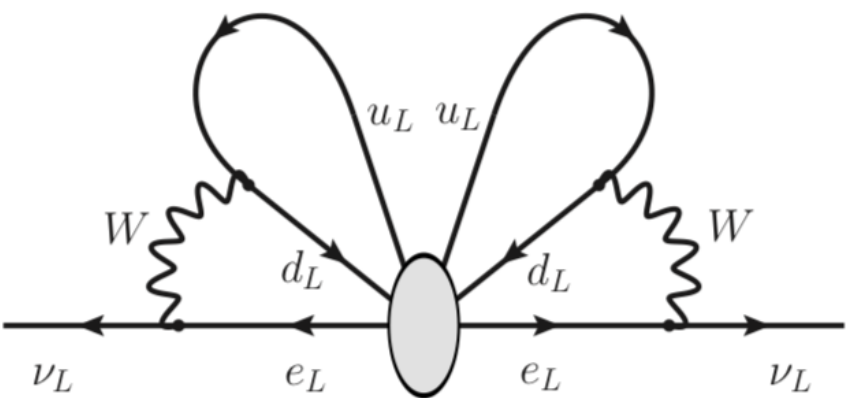
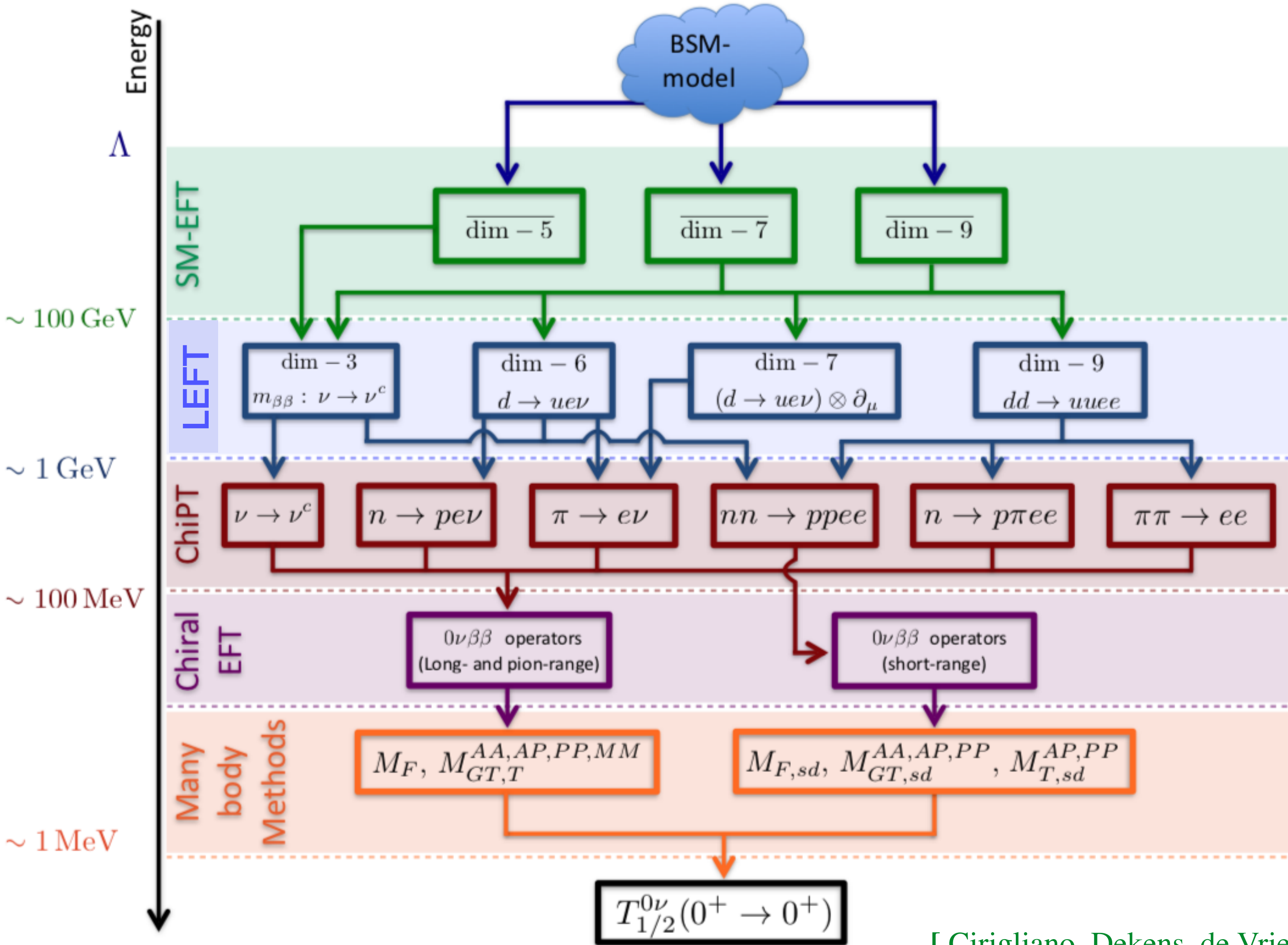
Dark matter EFT
Sterile neutrino EFT
Gravity EFT
Axion EFT
...

<https://abc4eft.hepforge.org/>

Jiang-Hao Yu (ITP-CAS)

EFT Framework for $0\nu\beta\beta$

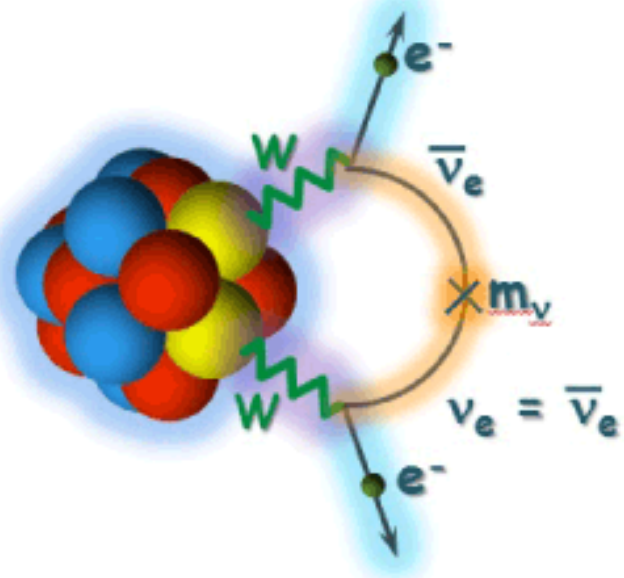
Tower of EFT bases from electroweak to nuclear scales



[Ramsey-Musolf, Yi Liao, Shao-Long Chen, Xiao-Dong Ma, Hao-Lin Wang, Gang Li, J.-H. Yu...]

[Jie Meng, Fu-Rong Xu, Peng Wei Zhao, Jiang-Ming Yao, Bing-Wei Long, Dong-Liang Fang, Jing-Yu Zhu...]

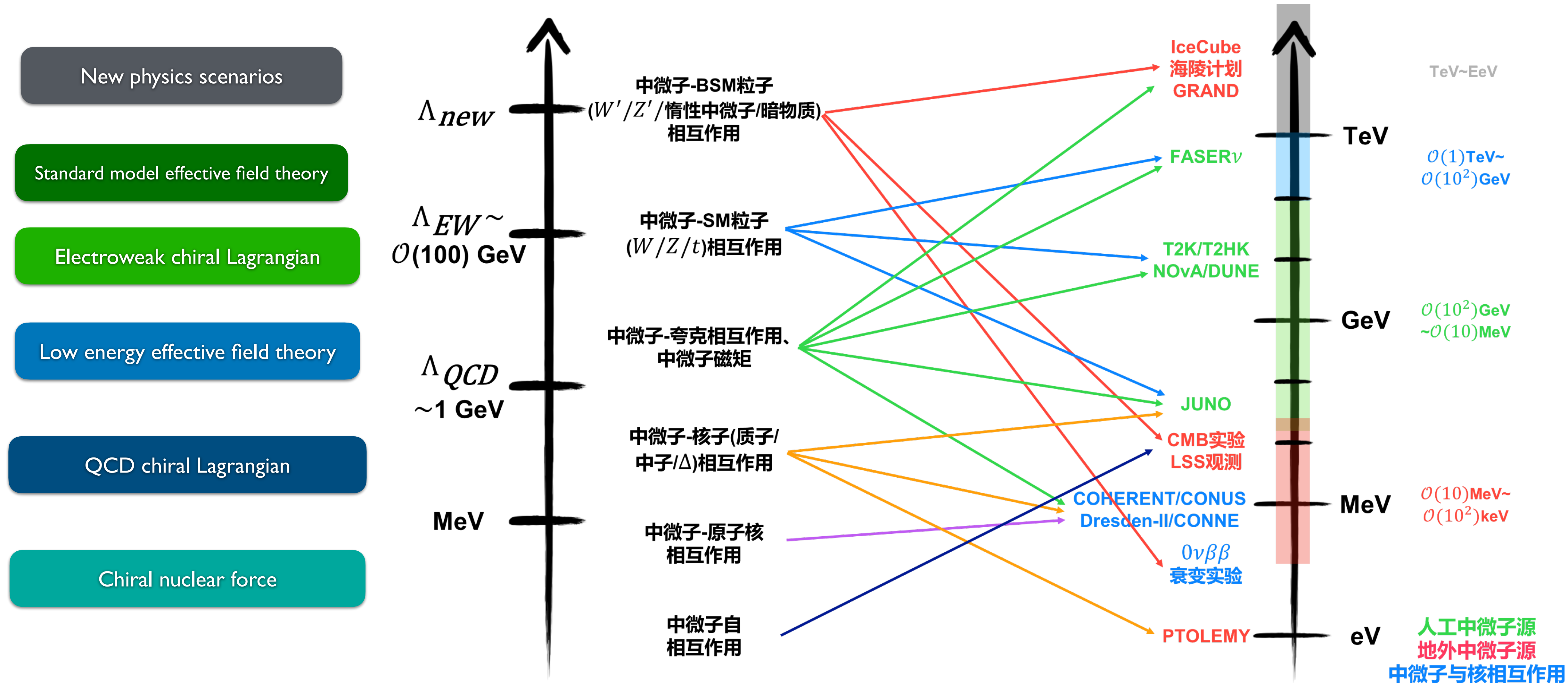
many-body theory	
exact	QMC, NCSM, ...
approximate	CC, IMSRG, MBPT, SCGF, ...
phenomenological	SM, DFT, ...
renormalization group (SRG, Okubo-Lee-Suzuki, ...)	



[Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2017]

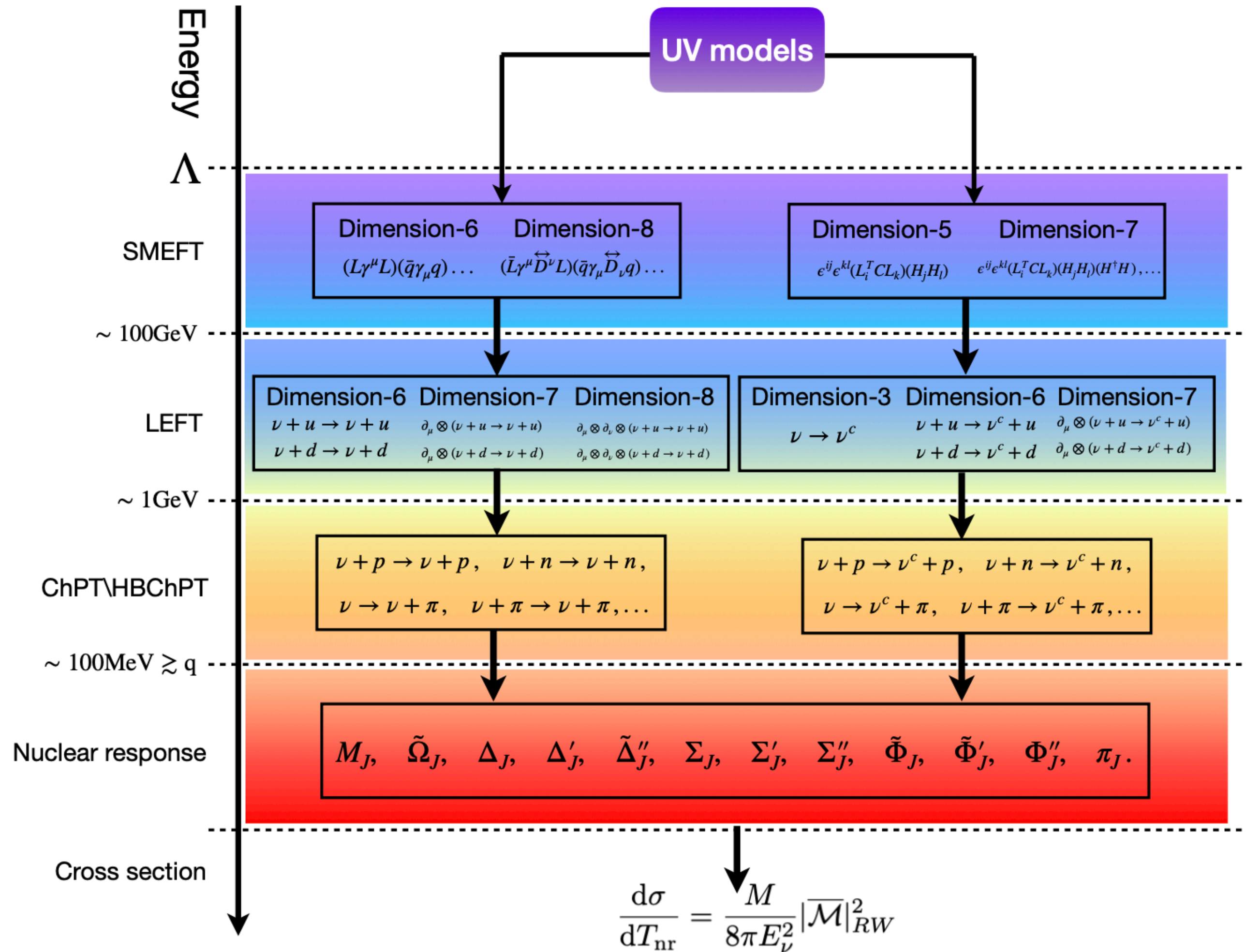
Neutrino interactions at different scales

Neutrino interactions are unified in the EFT framework

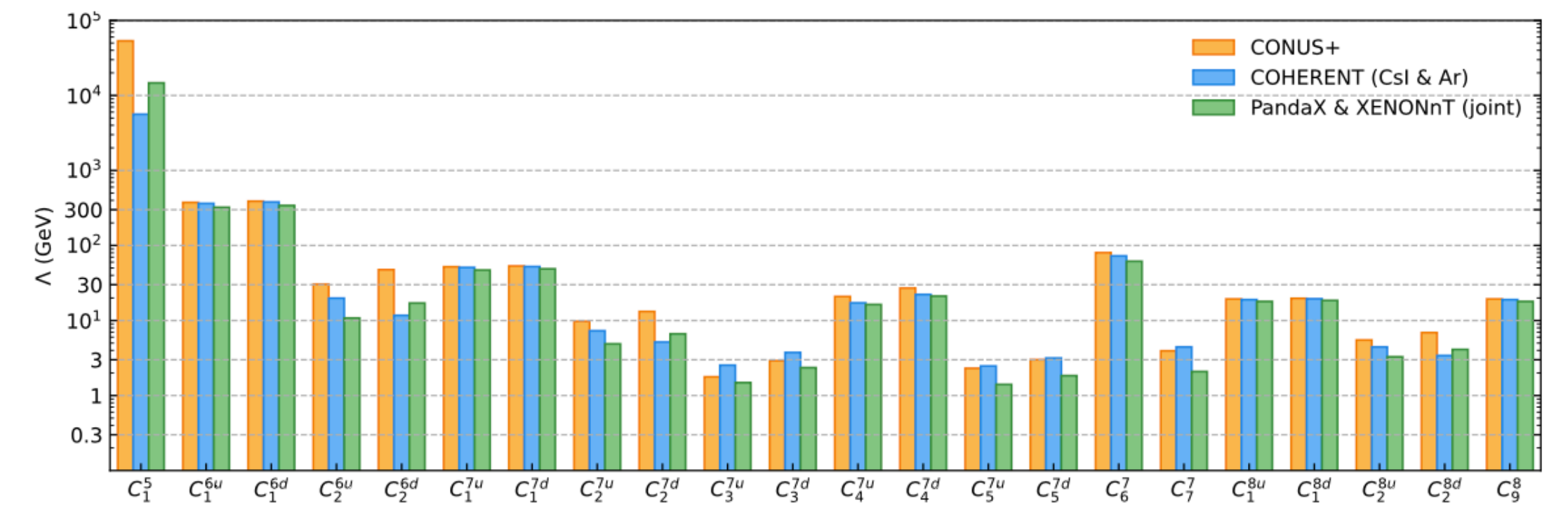


Coherent elastic neutrino nucleus scattering

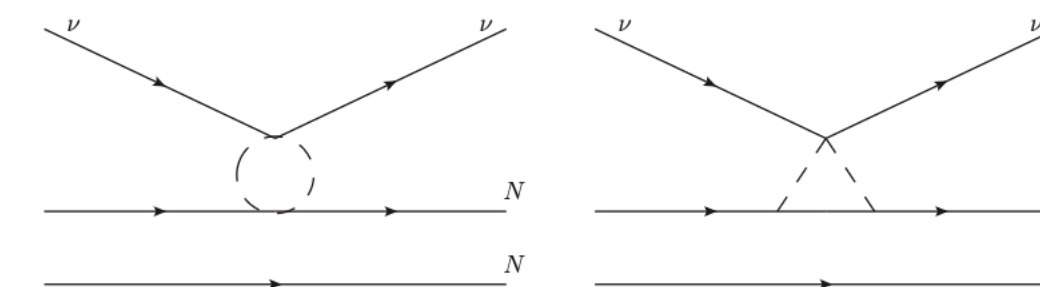
[Gang Li, Chuan-Qiang Song, Feng-Jie Tang, **J.H.Yu**, 2601.19883]



$$\begin{aligned} \mathcal{O}_1^{6u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma_\mu \tau^{u/d} q), & \mathcal{O}_2^{6u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^5 \gamma_\mu \tau^{u/d} q), \\ \mathcal{O}_1^{7u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \overleftrightarrow{D}_\mu \tau^{u/d} q), & \mathcal{O}_2^{7u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^5 \overleftrightarrow{D}_\mu \tau^{u/d} q), \\ \mathcal{O}_1^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta}) (\bar{q} \gamma_\mu \overleftrightarrow{D}_\nu \tau^{u/d} q), & \mathcal{O}_2^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta}) (\bar{q} \gamma^5 \gamma_\mu \overleftrightarrow{D}_\nu \tau^{u/d} q), \\ \mathcal{O}_3^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^\nu T^A \tau^{u/d} q) G_{\mu\nu}^A, & \mathcal{O}_4^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^5 \gamma^\nu T^A \tau^{u/d} q) G_{\mu\nu}^A, \\ \mathcal{O}_5^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) D^2 (\bar{q} \gamma_\mu \tau^{u/d} q), & \mathcal{O}_6^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) D^2 (\bar{q} \gamma^5 \gamma_\mu \tau^{u/d} q), \\ \mathcal{O}_7^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^\nu T^A \tau^{u/d} q) \tilde{G}_{\mu\nu}^A, & \mathcal{O}_8^{8u/d} &= (\bar{\nu}_{L\alpha} \gamma^\mu \nu_{L\beta}) (\bar{q} \gamma^5 \gamma^\nu T^A \tau^{u/d} q) \tilde{G}_{\mu\nu}^A, \\ \mathcal{O}_9^8 &= (\bar{\nu}_{L\alpha} \gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta}) G_{\mu\rho}^A G_\nu^{A\rho}, \end{aligned}$$

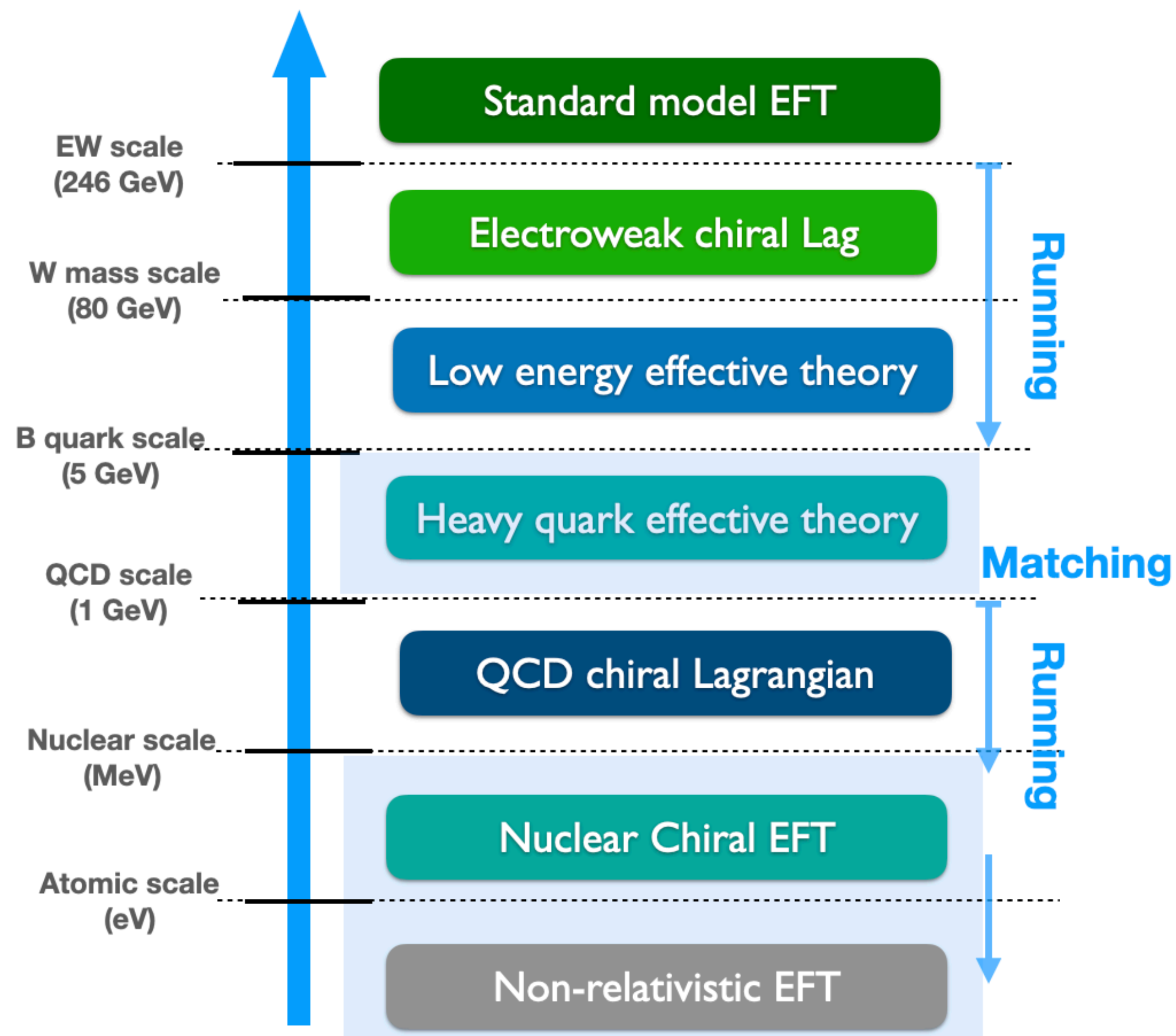


[Yu-Feng Li, Jia-Jun Liao, Shun Zhou, Yong-Cheng Wu, Gang Li, J.-H. Yu, ...]



Tower of EFTs at different scales

Describe collider physics, flavor physics, hadronic physics, nuclear physics and atomic physics



[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2007.07899]

[Hao-Lin Li, Jing Shu, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2005.00008]

[Zhe Ren, **J.H.Yu**, 2211.01420]

[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722]

[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2210.14939]

[Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2211.11598]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2105.09329]

[Huayang Song, Hao Sun, **J.H.Yu**, 2305.16770]

[Huayang Song, Hao Sun, **J.H.Yu**, 2306.05999]

[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047]

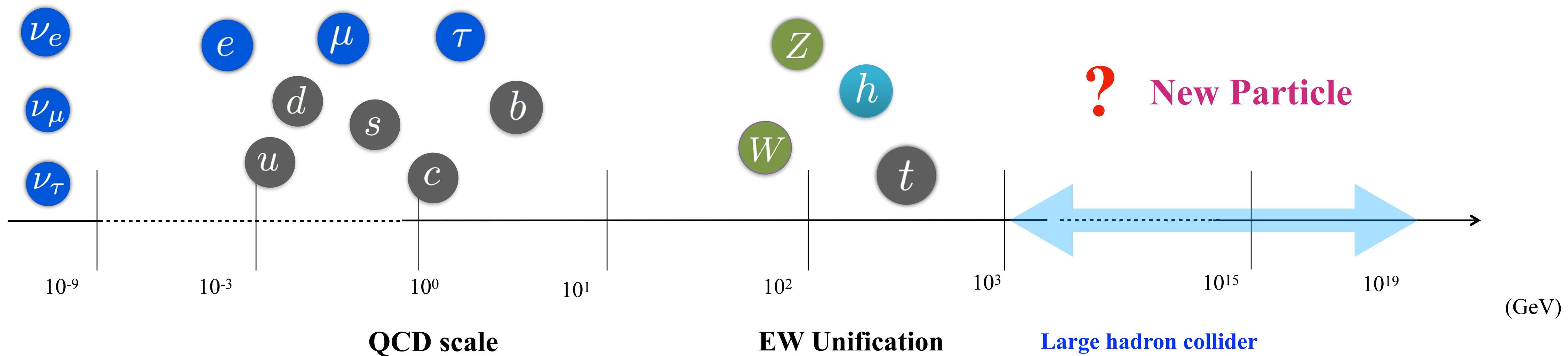
[Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152]

[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2501.09787]

[Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2501.14018]

[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, 2510.19929]

What's next?

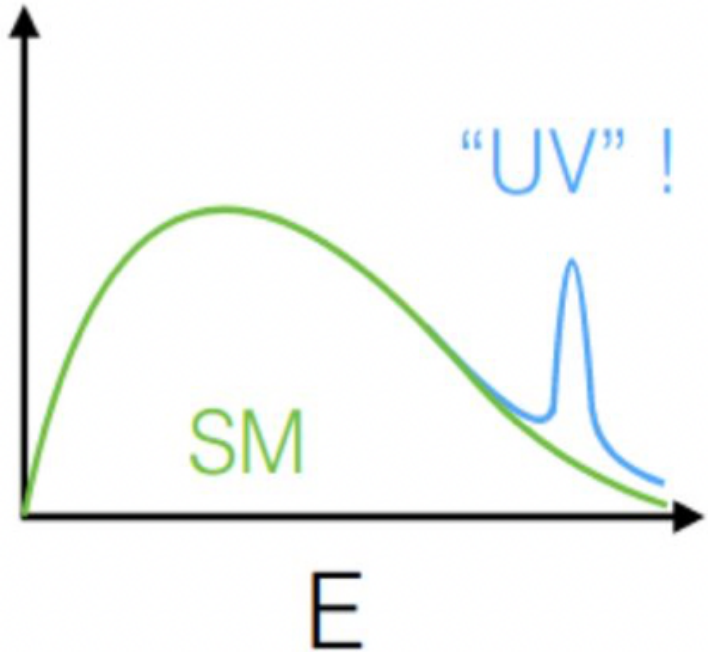
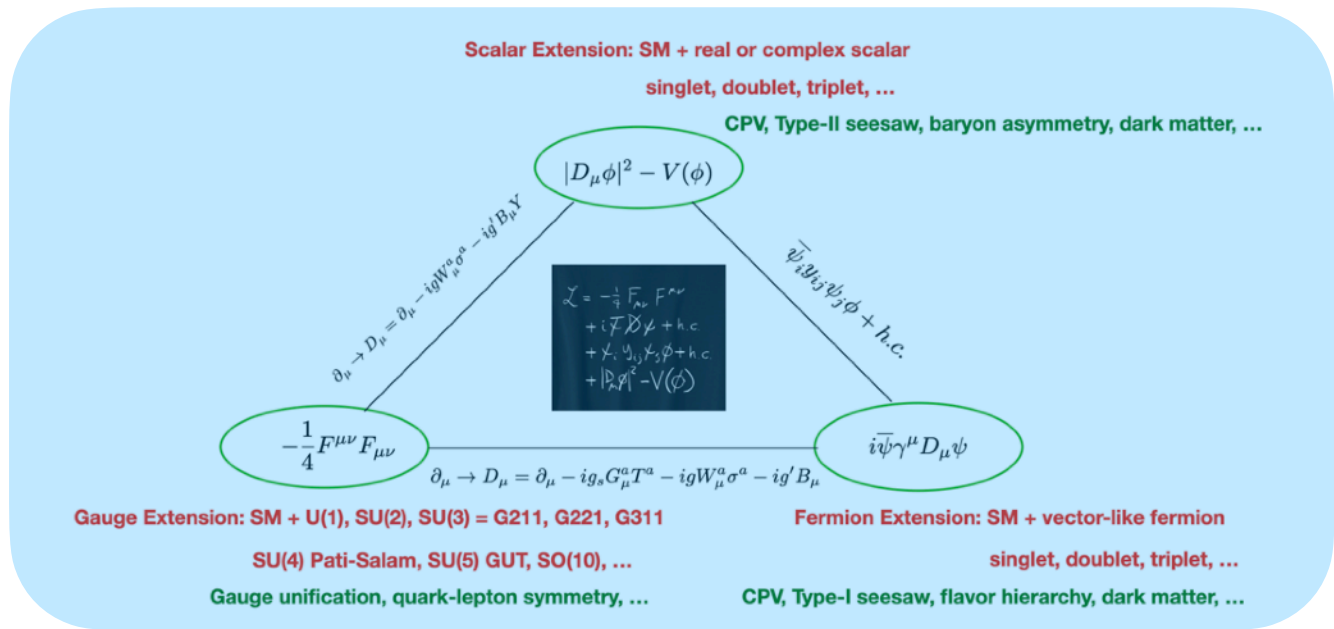


Given EFT operator sets, what is next?

Direct New Resonance Searches

From model to EFT and back ...

Thousand of new physics models



Very broad and too biased

top-down

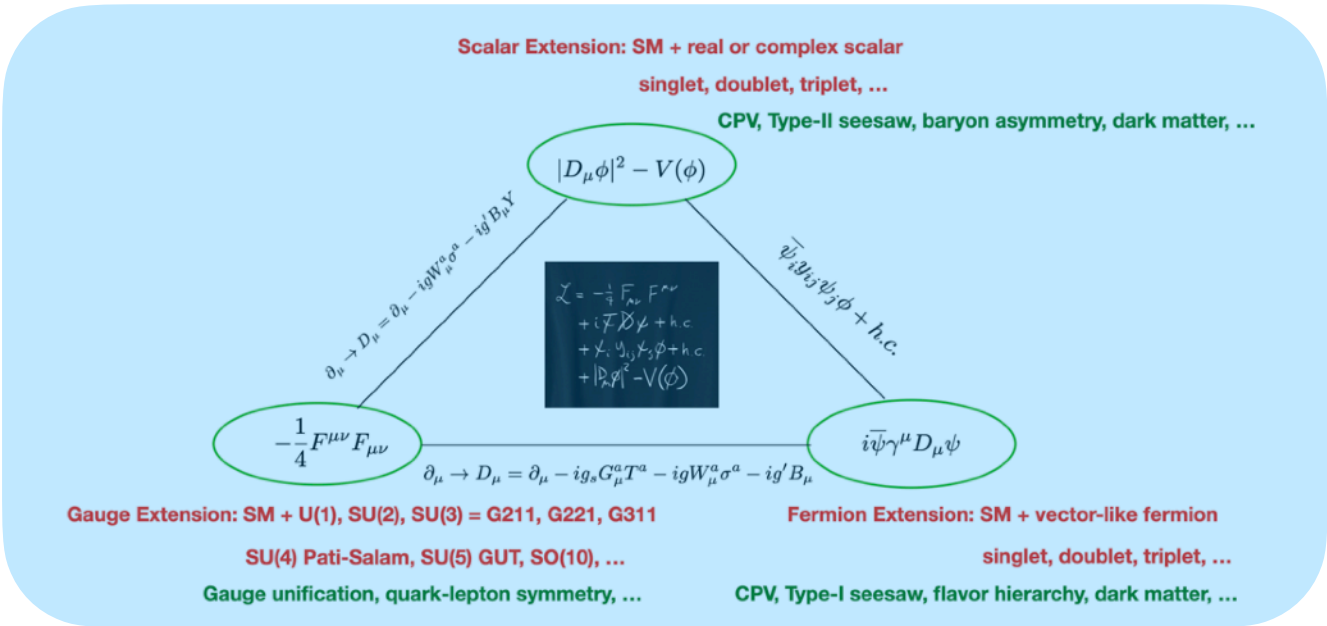
Bottom-up

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

A unique theory without new particle

From model to EFT and back ...

Thousand of new physics models



47 UV resonances from dim-6/7 operators

Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Operator	Interactions
0	1	1	0	$(H^\dagger H)(H^\dagger H)(H^\dagger H)$	$(H^\dagger H)S_1$
			1	$(H^\dagger H)\Box(H^\dagger H)$	
			2	$e^j_i e^l_k (\ell^{\dagger i} C \ell_j)(\ell^{\dagger k} C \ell^l_i)$	$e^{ij}(\ell^{\dagger}_i C \ell_j)S_2$
		2	1/2	$(e^{\dagger} C e)(\bar{e} C e^{\dagger})$	$(e^{\dagger} C e)S_3$
				$(H_j H^{\dagger j} H^{\dagger i})(H^{\dagger k} H_k H_i)$	$(H^\dagger H)(H^\dagger S_4)$
				$(H^{\dagger j} H_j H_i)(\bar{\ell}^i e)$	$(\bar{q}^i d)S_{4i}$
				$(H^{\dagger j} H_j H_i)(\bar{q}^i u)$	$(\bar{\ell}^i e)S_{4i}$
				$(H^{\dagger j} H_j H_i)(\bar{q}^i d)$	$e^{ij}(\bar{q}_i u)(\bar{q}_j d)$
				$e^{ij}(\bar{q}_i u)(\bar{q}_j d)$	$e^{ij}(\bar{u} q_j)S_{4i}$
				$e^{ij} e^{ik}(\bar{q}_i u)(\bar{u} q_k)$	$(\bar{\ell}^i e)(\bar{e} \ell_i)$
0	1	3	0	$(H^\dagger \tau^I H)(H^\dagger \tau^I H)(H^\dagger H)$	$(H^\dagger \tau^I H)S^I_5$
				$(H_i H^{\dagger j})(H_i H^{\dagger k})(H_k H^{\dagger j})$	$(H^\dagger H)(S^I_5 S^I_j)$
				$(H^\dagger \tau^I H)\Box(H^\dagger \tau^I H)$	$(\tau^I)_k^i (\tau^J)_j^k H_i H^{\dagger j} S^I_5 S^J_5$
				$(H^\dagger \tau^I H)(\bar{q} u \tau^I \bar{H})$	

Very broad and too biased

top-down

Bottom-up

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

A unique theory without new particle

From EFT operators to UV resonances

Generalized partial wave analysis of amplitudes

$$\mathcal{S} = \text{diagram 1} + \text{diagram 2} + \text{diagram 3} + \text{diagram 4} + \text{diagram 5} + \dots$$

$$\mathbf{W}^2 |P, J, \sigma\rangle = -P^2 J(J+1) |P, J, \sigma\rangle.$$



Pauli-Lubanski Partial Wave

$$\mathbf{W}^2 \text{diagram 6} = j_1(j_1+1) \text{diagram 7} + j_2(j_2+1) \text{diagram 8}$$

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

[Also Jiang, Shu, Xiao, Zheng]

Scattering amplitude based on on-shell particle

$$\mathcal{S} = \text{diagram 9} + \text{diagram 10} + \text{diagram 11} + \text{diagram 12} + \text{diagram 13} + \dots$$



Lagrangian based on local field

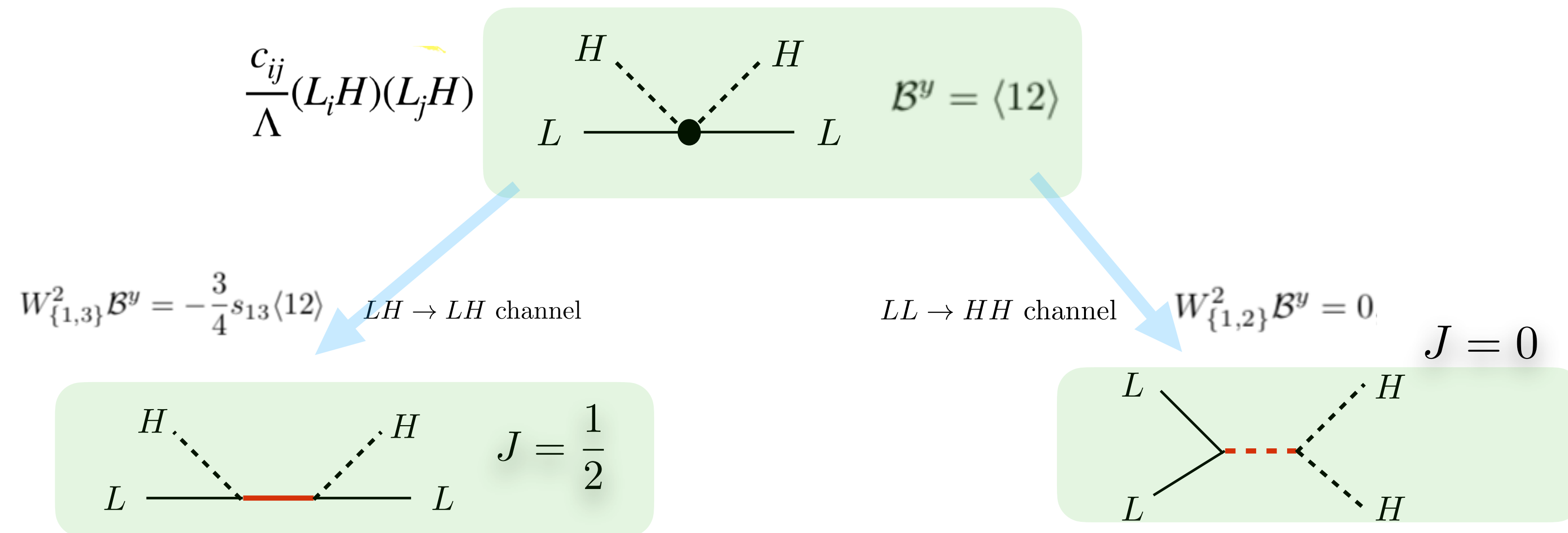
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \frac{\mathcal{L}_9}{\Lambda^5} + \dots$$

Dim-5 UVs: only 3 types of seesaw!

Partial wave analysis on simplest dim-5 Weinberg operator

Similar to $SO(3)$ angular J^2 , Poincare Pauli-Lubanski Casimir

$$\mathbf{W}^2 \mathcal{B}^J = -sJ(J+1)\mathcal{B}^J \quad [\text{Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, J.H.Yu, 2204.03660}]$$



Type-I and III: $SU(2)$ **single** and **triplet**

Type-II: $SU(2)$ **triplet**, or singlet (excluded by repeated field)

Complete dim-6 UVs

[Xu-Xiang Li, Zhe Ren, **J.H.Yu**, 2307.10380]

Generalized partial wave analysis for all the dim-6 operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_G	$f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	Q_{φ}	$(\varphi^{\dagger} \varphi)^3$	$Q_{e\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{l}_p e_r \varphi)$	Q_{ll}	$(\bar{l}_p \gamma_{\mu} l_r)(\bar{l}_s \gamma^{\mu} l_t)$	Q_{ee}	$(\bar{e}_p \gamma_{\mu} e_r)(\bar{e}_s \gamma^{\mu} e_t)$	Q_{le}	$(\bar{l}_p \gamma_{\mu} l_r)(\bar{e}_s \gamma^{\mu} e_t)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{\varphi \square}$	$(\varphi^{\dagger} \varphi) \square (\varphi^{\dagger} \varphi)$	$Q_{u\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{q}_p u_r \tilde{\varphi})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_{\mu} q_r)(\bar{q}_s \gamma^{\mu} q_t)$	Q_{uu}	$(\bar{u}_p \gamma_{\mu} u_r)(\bar{u}_s \gamma^{\mu} u_t)$	Q_{lu}	$(\bar{l}_p \gamma_{\mu} l_r)(\bar{u}_s \gamma^{\mu} u_t)$
Q_W	$\varepsilon^{IJK} W_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{\varphi D}$	$(\varphi^{\dagger} D^{\mu} \varphi)^{\star} (\varphi^{\dagger} D_{\mu} \varphi)$	$Q_{d\varphi}$	$(\varphi^{\dagger} \varphi)(\bar{q}_p d_r \varphi)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_{\mu} \tau^I q_r)(\bar{q}_s \gamma^{\mu} \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_{\mu} d_r)(\bar{d}_s \gamma^{\mu} d_t)$	Q_{ld}	$(\bar{l}_p \gamma_{\mu} l_r)(\bar{d}_s \gamma^{\mu} d_t)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$					$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_{\mu} l_r)(\bar{q}_s \gamma^{\mu} q_t)$	Q_{eu}	$(\bar{e}_p \gamma_{\mu} e_r)(\bar{u}_s \gamma^{\mu} u_t)$	Q_{qe}	$(\bar{q}_p \gamma_{\mu} q_r)(\bar{e}_s \gamma^{\mu} e_t)$
						$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_{\mu} \tau^I l_r)(\bar{q}_s \gamma^{\mu} \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_{\mu} e_r)(\bar{d}_s \gamma^{\mu} d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_{\mu} q_r)(\bar{u}_s \gamma^{\mu} u_t)$
								$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_{\mu} u_r)(\bar{d}_s \gamma^{\mu} d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_{\mu} T^A q_r)(\bar{u}_s \gamma^{\mu} T^A u_t)$
								$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_{\mu} T^A u_r)(\bar{d}_s \gamma^{\mu} T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_{\mu} q_r)(\bar{d}_s \gamma^{\mu} d_t)$
										$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_{\mu} T^A q_r)(\bar{d}_s \gamma^{\mu} T^A d_t)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B -violating			
$Q_{\varphi G}$	$\varphi^{\dagger} \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{l}_p \gamma^{\mu} l_r)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^{\alpha})^T C u_r^{\beta}] [(q_s^{\gamma j})^T C l_t^k]$		
$Q_{\varphi \tilde{G}}$	$\varphi^{\dagger} \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu}^I \varphi)(\bar{l}_p \tau^I \gamma^{\mu} l_r)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^{\gamma})^T C e_t]$		
$Q_{\varphi W}$	$\varphi^{\dagger} \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{e}_p \gamma^{\mu} e_r)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jn} \varepsilon_{km} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$		
$Q_{\varphi \tilde{W}}$	$\varphi^{\dagger} \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{q}_p \gamma^{\mu} q_r)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^{\alpha})^T C u_r^{\beta}] [(u_s^{\gamma})^T C e_t]$		
$Q_{\varphi B}$	$\varphi^{\dagger} \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu}^I \varphi)(\bar{q}_p \tau^I \gamma^{\mu} q_r)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$				
$Q_{\varphi \tilde{B}}$	$\varphi^{\dagger} \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{u}_p \gamma^{\mu} u_r)$						
$Q_{\varphi WB}$	$\varphi^{\dagger} \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^{\dagger} i \overleftrightarrow{D}_{\mu} \varphi)(\bar{d}_p \gamma^{\mu} d_r)$						
$Q_{\varphi \tilde{W}B}$	$\varphi^{\dagger} \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^{\dagger} D_{\mu} \varphi)(\bar{u}_p \gamma^{\mu} d_r)$						

Dim-6 operators and UVs

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}
$\mathcal{O}_H$	✓			✓	✓	✓	✓	✓											
$\mathcal{O}_{H\Box}$	✓				✓	✓													
$\mathcal{O}_{HD}$					✓	✓													
$\mathcal{O}_{eH}$	*			✓	✓	✓													
$\mathcal{O}_{uH}$	*			✓	✓	✓													
$\mathcal{O}_{dH}$	*			✓	✓	✓													
$\mathcal{O}_{ll}$		✓				✓													
$\mathcal{O}_{qq}^{(1)}$										✓				✓		✓		✓	
$\mathcal{O}_{qq}^{(3)}$										✓				✓		✓		✓	
$\mathcal{O}_{lq}^{(1)}$										✓				✓					
$\mathcal{O}_{lq}^{(3)}$										✓				✓					
$\mathcal{O}_{ee}$			✓																
$\mathcal{O}_{uu}$									✓								✓		
$\mathcal{O}_{dd}$											✓				✓				
$\mathcal{O}_{eu}$										✓									
$\mathcal{O}_{ed}$									✓										
$\mathcal{O}_{ud}^{(1)}$										✓									
$\mathcal{O}_{ud}^{(8)}$										✓									
$\mathcal{O}_{le}$				✓															
$\mathcal{O}_{lu}$																			
$\mathcal{O}_{ld}$												✓							
$\mathcal{O}_{qe}$																			
$\mathcal{O}_{qu}^{(1)}$				✓															
$\mathcal{O}_{qu}^{(8)}$				✓															
$\mathcal{O}_{qd}^{(1)}$				✓															
$\mathcal{O}_{qd}^{(8)}$				✓															
$\mathcal{O}_{ledq}$				✓															
$\mathcal{O}_{quqd}^{(1)}$				✓						✓									
$\mathcal{O}_{quqd}^{(8)}$										✓									
$\mathcal{O}_{lequ}^{(1)}$				✓						✓									
$\mathcal{O}_{lequ}^{(3)}$										✓			✓						
$\mathcal{O}_{duq}$										✓									
$\mathcal{O}_{qqu}$										✓									
$\mathcal{O}_{qqq}$										✓				✓					
$\mathcal{O}_{duu}$									✓	✓									

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	F_{14}
$\mathcal{O}_{eH}$		✓	✓	✓	✓	✓								
$\mathcal{O}_{uH}$									✓		✓	✓	✓	✓
$\mathcal{O}_{dH}$								✓		✓	✓		✓	✓
$\mathcal{O}_{Hl}^{(1)}$	✓	✓			✓	✓								
$\mathcal{O}_{Hl}^{(3)}$	✓	✓			✓	✓								
$\mathcal{O}_{He}$			✓	✓										
$\mathcal{O}_{Hq}^{(1)}$								✓	✓				✓	✓
$\mathcal{O}_{Hq}^{(3)}$								✓	✓				✓	✓
$\mathcal{O}_{Hu}$											✓	✓		
$\mathcal{O}_{Hd}$										✓	✓			
$\mathcal{O}_{Hud}$											✓			

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}
$\mathcal{O}_H$		✓		✓										
$\mathcal{O}_{H\Box}$	✓	✓		✓										
$\mathcal{O}_{HD}$	✓	✓		✓										
$\mathcal{O}_{eH}$	✓	✓		✓										
$\mathcal{O}_{uH}$	✓	✓		✓										
$\mathcal{O}_{dH}$	✓	✓		✓										
$\mathcal{O}_{Hl}^{(1)}$	✓													
$\mathcal{O}_{Hl}^{(3)}$				✓										
$\mathcal{O}_{He}$	✓													
$\mathcal{O}_{Hq}^{(1)}$	✓													
$\mathcal{O}_{Hq}^{(3)}$				✓										
$\mathcal{O}_{Hu}$	✓													
$\mathcal{O}_{Hd}$	✓													
$\mathcal{O}_{Hud}$		✓												
$\mathcal{O}_{ll}$	✓			✓										
$\mathcal{O}_{qq}^{(1)}$	✓												✓	✓
$\mathcal{O}_{qq}^{(3)}$				✓									✓	✓
$\mathcal{O}_{lq}^{(1)}$	✓				✓							✓		
$\mathcal{O}_{lq}^{(3)}$				✓	✓							✓		
$\mathcal{O}_{ee}$	✓													
$\mathcal{O}_{qu}^{(1)}$														
$\mathcal{O}_{qu}^{(8)}$													✓	
$\mathcal{O}_{le}$				✓									✓	
$\mathcal{O}_{lu}$														
$\mathcal{O}_{ld}$														
$\mathcal{O}_{qe}$														
$\mathcal{O}_{qu}^{(1)}$				✓										
$\mathcal{O}_{qu}^{(8)}$				✓										
$\mathcal{O}_{qd}^{(1)}$				✓										
$\mathcal{O}_{qd}^{(8)}$				✓										
$\mathcal{O}_{ledq}$				✓										
$\mathcal{O}_{quqd}^{(1)}$				✓										
$\mathcal{O}_{quqd}^{(8)}$														
$\mathcal{O}_{lequ}^{(1)}$				✓										
$\mathcal{O}_{lequ}^{(3)}$														
$\mathcal{O}_{duq}$														
$\mathcal{O}_{qqu}$														
$\mathcal{O}_{qqq}$														
$\mathcal{O}_{duu}$														

Dim-7 seesaw UVs

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

59 UV tree-level models, 19 topologies, one genuine dim-7 seesaw

Topology	j-basis	Quantum numbers $\{J, \mathbf{R}, Y\}$
	$\mathcal{O}_{\{12 34 56\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p,$	$\{0, 3, -1\}, \{0, 3, 1\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 34 56\},2} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 1, 1\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 34 56\},3} = 12\mathcal{O}_4^p,$	$\{0, 1, -1\}, \{0, 3, 1\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 34 56\},4} = 4\mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0, 3, -1\}, \{0, 3, 1\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{12 34 56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$	$\{0, 1, -1\}, \{0, 1, 1\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{13 24 56\},1} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 3, 0\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 24 56\},2} = -\mathcal{O}_1^p + 3\mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 1, 0\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 24 56\},3} = -\mathcal{O}_1^p + \mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 3, 0\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 24 56\},4} = -\mathcal{O}_1^p - \mathcal{O}_2^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 3, 0\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{13 24 56\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 1, 0\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{16 23 45\},1} = 2\mathcal{O}_1^p - 2\mathcal{O}_2^p - 2\mathcal{O}_3^p + 6\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 3, 0\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 23 45\},2} = -2\mathcal{O}_1^p - \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 1, 0\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 23 45\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 3, 0\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 23 45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 3, 0\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{16 23 45\},5} = \mathcal{O}_2^p - \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 1, 0\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{12 125 34\},1} = \mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0, 3, -1\}, \{0, 4, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 125 34\},2} = -8\mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 125 34\},3} = -12\mathcal{O}_4^p,$	$\{0, 1, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 125 34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{12 125 34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$	$\{0, 1, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{12 126 34\},1} = 3\mathcal{O}_1^p,$	$\{0, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 126 34\},2} = 12\mathcal{O}_2^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 126 34\},3} = -12\mathcal{O}_4^p,$	$\{0, 1, -1\}, \{0, 2, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{12 126 34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{3}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{12 126 34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$	$\{0, 1, -1\}, \{0, 2, -\frac{3}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{12 124 36\},1} = -\mathcal{O}_1^p - 4\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 4, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 124 36\},2} = 2\mathcal{O}_1^p + 6\mathcal{O}_2^p + 2\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 124 36\},3} = -6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$	$\{0, 1, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{12 124 36\},4} = -2\mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p,$	$\{0, 3, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{12 124 36\},5} = -2\mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{0, 1, -1\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{13 135 24\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p - 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 4, \frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{13 135 24\},2} = -\mathcal{O}_1^p - 3\mathcal{O}_2^p - 4\mathcal{O}_3^p + 9\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{13 135 24\},3} = \mathcal{O}_1^p - \mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{13 135 24\},4} = \mathcal{O}_1^p - 3\mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{\frac{1}{2}, 1, 0\}$
	$\mathcal{O}_{\{13 135 24\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{\frac{1}{2}, 1, 0\}$
	$\mathcal{O}_{\{16 146 23\},1} = -2\mathcal{O}_1^p + 4\mathcal{O}_3^p - 12\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 4, -\frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{16 146 23\},2} = 2\mathcal{O}_1^p - 3\mathcal{O}_2^p - \mathcal{O}_3^p + 9\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{16 146 23\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{\frac{1}{2}, 3, 0\}$
	$\mathcal{O}_{\{16 146 23\},4} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{\frac{1}{2}, 1, 0\}$
	$\mathcal{O}_{\{16 146 23\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p - \mathcal{O}_4^p + \mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{\frac{1}{2}, 1, 0\}$

	$\mathcal{O}_{\{13 123 45\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 4, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 123 45\},2} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 9\mathcal{O}_4^p - 9\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 123 45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 123 45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{13 123 45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{13 123 46\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 4, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 123 46\},2} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 9\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 123 46\},3} = -\mathcal{O}_1^p - 2\mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{13 123 46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{0, 4, -\frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{13 123 46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{0, 2, -\frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{16 126 34\},1} = 6\mathcal{O}_1^p,$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 126 34\},2} = -3\mathcal{O}_2^p + 9\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 126 34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 126 34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 126 34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{23 235 46\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 4, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{23 235 46\},2} = \mathcal{O}_1^p - 6\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{23 235 46\},3} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{23 235 46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 6\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{23 235 46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 2\mathcal{O}_4^p + \mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{13 136 45\},1} = \mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p - 6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 4, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 136 45\},2} = 2\mathcal{O}_1^p - 5\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 136 45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{13 136 45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, 0\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{13 136 45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, 0\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{16 156 34\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p + 12\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 4, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 156 34\},2} = 4\mathcal{O}_1^p + \mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 156 34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 3, 1\}$
	$\mathcal{O}_{\{16 156 34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2}, 3, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{16 156 34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2}, 1, -1\}, \{\frac{1}{2}, 2, -\frac{1}{2}\}, \{0, 1, 1\}$
	$\mathcal{O}_{\{34 134 56\},1} = -\mathcal{O}_1^p + 2\mathcal{O}_2^p + 6\mathcal{O}_4^p,$	$\{0, 3, 1\}, \{\frac{1}{2}, 4, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{34 134 56\},2} = 4\mathcal{O}_1^p - 8\mathcal{O}_2^p + 12\mathcal{O}_4^p,$	$\{0, 3, 1\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{34 134 56\},3} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$	$\{0, 1, 1\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 3, 0\}$
	$\mathcal{O}_{\{34 134 56\},4} = -4\mathcal{O}_1^p - 4\mathcal{O}_2^p,$	$\{0, 3, 1\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{34 134 56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$	$\{0, 1, 1\}, \{\frac{1}{2}, 2, \frac{1}{2}\}, \{0, 1, 0\}$
	$\mathcal{O}_{\{16 126\},1} = 6\mathcal{O}_1^p,$	$\{\frac{1}{2}, 3, -1\}, \{0, 4, -\frac{3}{2}\}$
	$\mathcal{O}_{\{16 126\},2,3} = \begin{pmatrix} \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p \end{pmatrix},$	$\{\frac{1}{2}, 3, -1\}, \{0, 2, -\frac{3}{2}\}$
	$\mathcal{O}_{\{16 126\},4,5} = \begin{pmatrix} -\mathcal{O}_2^p - 2\mathcal{O}_3^p - \mathcal{O}_4^p - 2\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p \end{pmatrix}.$	$\{\frac{1}{2}, 1, -1\}, \{0, 2, -\frac{3}{2}\}$

[Bonnet, Hernandez, Ota, Winter, 2009]

Systematic resonance searches at the LHC

From partial wave analysis , there are only 47 resonances with leading effects at the LHC

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3}$$

Tree-level origin of all dim-5/6/7 operators

[Xu-Xiang Li, Zhe Ren, **J.H.Yu**, 2307.10380]

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Scalars

Notation	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{1})_2$	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{1}, \mathbf{3})_1$	$(\mathbf{1}, \mathbf{4})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{4})_{\frac{3}{2}}$
Notation	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}		
Name	ω_4	ω_1	ω_2	Π_1	Π_7	ζ		
Irrep	$(\mathbf{3}, \mathbf{1})_{-\frac{4}{3}}$	$(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}, \mathbf{3})_{-\frac{1}{3}}$		
Notation	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}			
Name	Ω_2	Ω_1	Ω_4	Υ_1	Φ			
Irrep	$(\mathbf{6}, \mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{6}, \mathbf{1})_{\frac{1}{3}}$	$(\mathbf{6}, \mathbf{1})_{\frac{4}{3}}$	$(\mathbf{6}, \mathbf{3})_{\frac{1}{3}}$	$(\mathbf{8}, \mathbf{2})_{\frac{1}{2}}$			

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Fermions

Notation	F_1	F_2	F_3	F_4	F_5	F_6	F_7
Name	N	E^c	Δ_1^c	Δ_3^c	Σ	Σ_1^c	
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{1}, \mathbf{3})_1$	$(\mathbf{1}, \mathbf{4})_{\frac{1}{2}}$
Notation	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	F_{14}
Name	D	U	Q_5	Q_1	Q_7	T_1	T_2
Irrep	$(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}, \mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{3})_{\frac{2}{3}}$

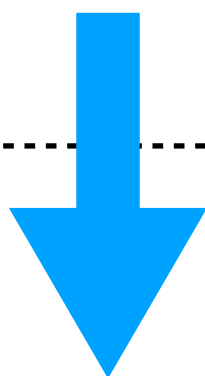
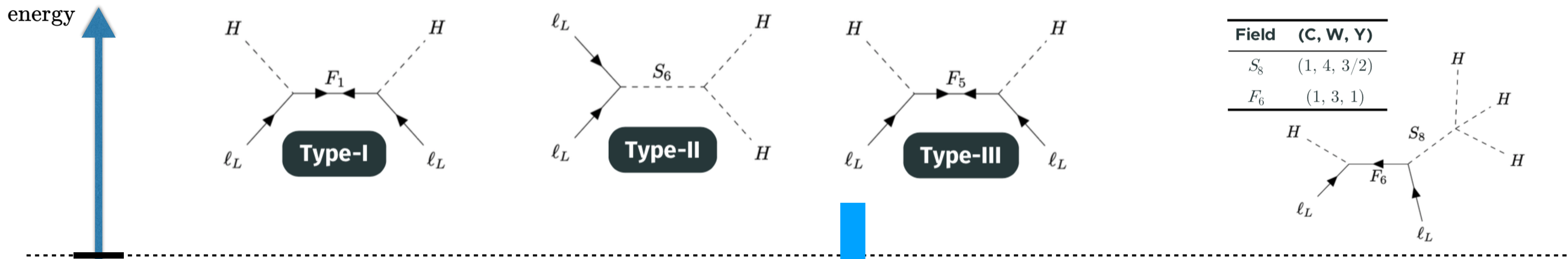
14
Vectors

Notation	V_1	V_2	V_3	V_4	V_5	V_6	V_7
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{L}_3^\dagger$	$\mathcal{W}$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_5$
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{5}{3}}$	$(\mathbf{3}, \mathbf{2})_{-\frac{5}{6}}$
Notation	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}
Name	$\mathcal{Q}_1$	$\mathcal{X}$	$\mathcal{Y}_1^\dagger$	$\mathcal{Y}_5^\dagger$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$
Irrep	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{3})_{\frac{2}{3}}$	$(\mathbf{6}, \mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{6}, \mathbf{2})_{\frac{5}{6}}$	$(\mathbf{8}, \mathbf{1})_0$	$(\mathbf{8}, \mathbf{1})_1$	$(\mathbf{8}, \mathbf{3})_0$

Effective way of search new physics: symmetry determines new resonances!

One-loop matching for seesaw

[Xu-Xiang Li, Zhe Ren, **J.H.Yu**, 2307.10380]



Operators	F_1	S_6	F_5	$S_8 \& F_6$	$0\nu\beta\beta$	other
$\mathcal{O}_5$	✓	✓	✓	✗	✓	
$\mathcal{O}_H$	✗	✓	✗	✓		
$\mathcal{O}_{H\Box}$	✗	✓	✗	✗		
$\mathcal{O}_{HD}$	✗	✓	✗	✗		
$\mathcal{O}_{eH}$	✗	✓	✓	✗		
$\mathcal{O}_{uH}$	✗	✓	✗	✗		
$\mathcal{O}_{dH}$	✗	✓	✗	✗		
$\mathcal{O}_{Hl}^{(1)}$	✓	✗	✓	✓		
$\mathcal{O}_{Hl}^{(3)}$	✓	✗	✓	✓		
$\mathcal{O}_{ll}$	✗	✓	✗	✗		
$\mathcal{O}_{LH}$	✓	✓	✓	✓	✓	τ
$\mathcal{O}_{LeHD}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{LHD1}$	✗	✓	✓	✗	✓	τ, K
$\mathcal{O}_{LHD2}$	✓	✓	✓	✗	✗	τ
$\mathcal{O}_{LHW}$	✓	✗	✓	✗	✓	τ, K, Dip
$\mathcal{O}_{LHB}$	✗	✗	✗	✗	✗	Dip
$\mathcal{O}_{eLLLH}$	✓	✗	✓	✗	✗	τ
$\mathcal{O}_{dLQLH1}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{dLQLH2}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{QuLLH}$	✓	✗	✓	✗	✓	τ

Operators	Seesaw models			$Y_{\nu,\Sigma} \stackrel{?}{=} 0$
	Type-I	Type-II	Type-III	
One-loop matching				
$\mathcal{O}_W$	$\times$	$\checkmark$	$\checkmark(-N_\Sigma)$	No
$\mathcal{O}_{HW}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{HB}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{HWB}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{eW}$	$\checkmark$	$\checkmark(-\frac{9}{5})$	$\checkmark(\frac{9}{5})$	No
$\mathcal{O}_{eB}$	$\checkmark$	$\checkmark(6)$	$\checkmark(3)$	No
$\mathcal{O}_{Hl}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{Hl}^{(3)}$	$\times$	$\checkmark$	$\checkmark$	Yes
$\mathcal{O}_{Hq}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{Hq}^{(3)}$	$\times$	$\checkmark$	$\checkmark$	Yes
$\mathcal{O}_{ll}$	$\times$	$\checkmark$	$\checkmark$	Yes
$\mathcal{O}_{qq}^{(1)}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{qq}^{(3)}$	$\times$	$\checkmark$	$\checkmark(4N_\Sigma)$	No
$\mathcal{O}_{lq}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{lq}^{(3)}$	$\times$	$\checkmark$	$\checkmark(4N_\Sigma)$	Yes
$\mathcal{O}_{ee}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{uu}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{dd}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{eu}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{ed}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{ud}^{(1)}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{le}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{lu}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{ld}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{qe}$	$\times$	$\checkmark$	$\times$	No
$\mathcal{O}_{qu}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{qu}^{(8)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{qd}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{qd}^{(8)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{ledq}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{quqd}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes
$\mathcal{O}_{lequ}^{(1)}$	$\times$	$\checkmark$	$\times$	Yes

One-loop CDE

[Du, Li, **Yu**, 2201.04646]

[Zhang, Zhou, 2107.12133]

[Li, Zhang, Zhou, 2201.05082]

[Liao, Ma, 2210.04270]

Complete dim-8 UVs and positivity

[Cen Zhang, Shuang-Yong Zhou, Jia-Ying Gu, ...]

Type: $\mathcal{D}^4 H^2 H^{\dagger 2}$		
$\mathcal{O}_1^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H_i H_j (D_\mu D_\nu H^{\dagger i}) (D^\mu D^\nu H^{\dagger j})$,		
$\mathcal{O}_2^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H^{\dagger i} H_i (D_\mu D_\nu H_j) (D^\mu D^\nu H^{\dagger j})$,		
$\mathcal{O}_3^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H_i (D_\mu H_j) (D_\nu H^{\dagger i}) (D^\mu D^\nu H^{\dagger j})$.		
group: $(\text{Spin}, SU(3)_c, SU(2)_w, U(1)_y)$		
	$\{H_1, H_2\}, \{H^\dagger_3, H^\dagger_4\}$	
*	(2, 1, 3, 1)	$-8\mathcal{O}_1^f - 48\mathcal{O}_2^f - 48\mathcal{O}_3^f$
	(0, 1, 3, 1)	$8\mathcal{O}_1^f$
	(1, 1, 1, 1)	$8\mathcal{O}_1^f + 16\mathcal{O}_3^f$
	$\{H_1, H^\dagger_3\}, \{H_2, H^\dagger_4\}$	
*	(2, 1, 3, 0)	$16\mathcal{O}_1^f - 4\mathcal{O}_2^f + 56\mathcal{O}_3^f$
	(1, 1, 3, 0)	$8\mathcal{O}_1^f - 4\mathcal{O}_2^f + 8\mathcal{O}_3^f$
	(0, 1, 3, 0)	$8\mathcal{O}_1^f + 4\mathcal{O}_2^f + 16\mathcal{O}_3^f$
*	(2, 1, 1, 0)	$-24\mathcal{O}_1^f - 4\mathcal{O}_2^f - 24\mathcal{O}_3^f$
	(1, 1, 1, 0)	$-4\mathcal{O}_2^f - 8\mathcal{O}_3^f$
	(0, 1, 1, 0)	$4\mathcal{O}_2^f$

[C.Yang, Z. Ren, J.H. Yu, 2312.04663]

In the forward limit, a twice-subtracted dispersion relation

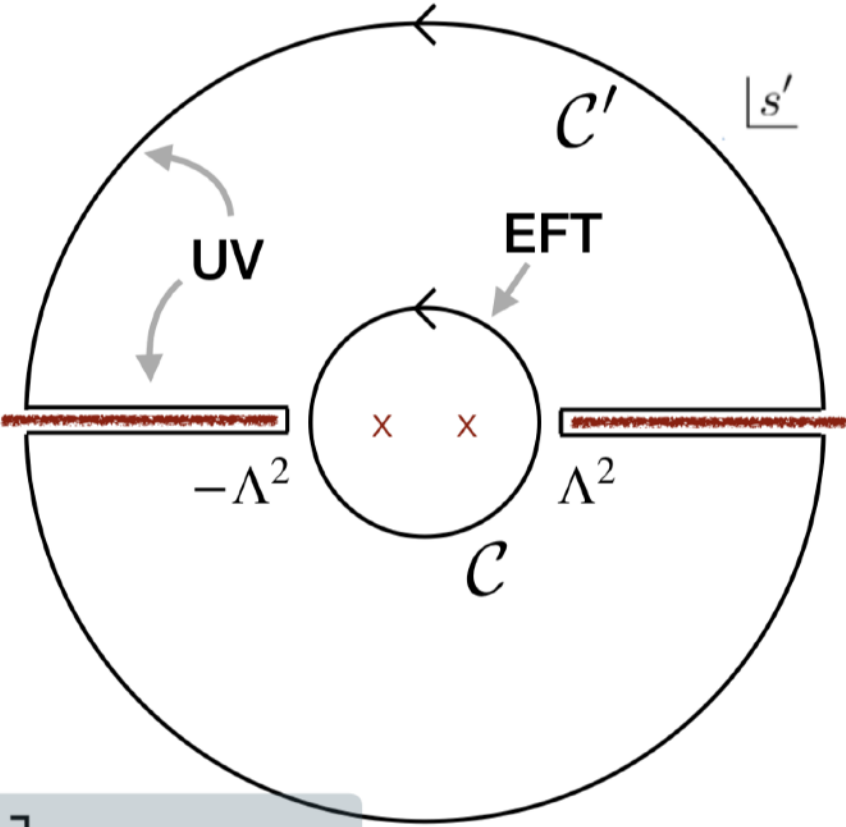
$$\mathcal{M}^{ijkl} = \frac{1}{2\pi} \int_{(\epsilon\Lambda)^2}^{\infty} \frac{ds}{s^3} \sum_X [\mathbf{M}_{ij \rightarrow X} \mathbf{M}_{kl \rightarrow X}^* + (j \leftrightarrow l)]$$

Particle	Spin	Charge/irrep	Interaction	ER	$\vec{c}$	$\vec{c}^{(6)}$
$\mathcal{B}_1$	1	1_1	$g\mathcal{B}_1^{\mu\dagger} (H^T \epsilon \overleftrightarrow{D}_\mu H) + h.c.$	✓	$8(1, 0, -1)$	$2(-1, 2)$
Ξ_1	0	3_1	$gM\Xi_1^{I\dagger} (H^T \epsilon \tau^I H) + h.c.$	✗	$8(0, 1, 0)$	$2(1, 2)$
$\mathcal{S}$	0	$1_0(S)$	$gMS (H^\dagger H)$	✓	$2(0, 0, 1)$	$-\frac{1}{2}(1, 0)$
$\mathcal{B}$	1	$1_0(A)$	$g\mathcal{B}^\mu (H^\dagger \overleftrightarrow{D}_\mu H)$	✓	$2(-1, 1, 0)$	$-\frac{1}{2}(1, 4)$
Ξ_0	0	$3_0(S)$	$gM\Xi_0^I (H^\dagger \tau^I H)$	✗	$2(2, 0, -1)$	$\frac{1}{2}(1, -4)$
$\mathcal{W}$	1	$3_0(A)$	$g\mathcal{W}^{\mu I} (H^\dagger \tau^I \overleftrightarrow{D}_\mu H)$	✗	$2(1, 1, -2)$	$-\frac{3}{2}(1, 0)$

Analyticity in complex s plane (fixed t)

$$A(s, t) = \frac{1}{2\pi i} \oint_C ds' \frac{A(s', t)}{s' - s}$$

Cauchy's integral formula



Fixed t dispersion relation

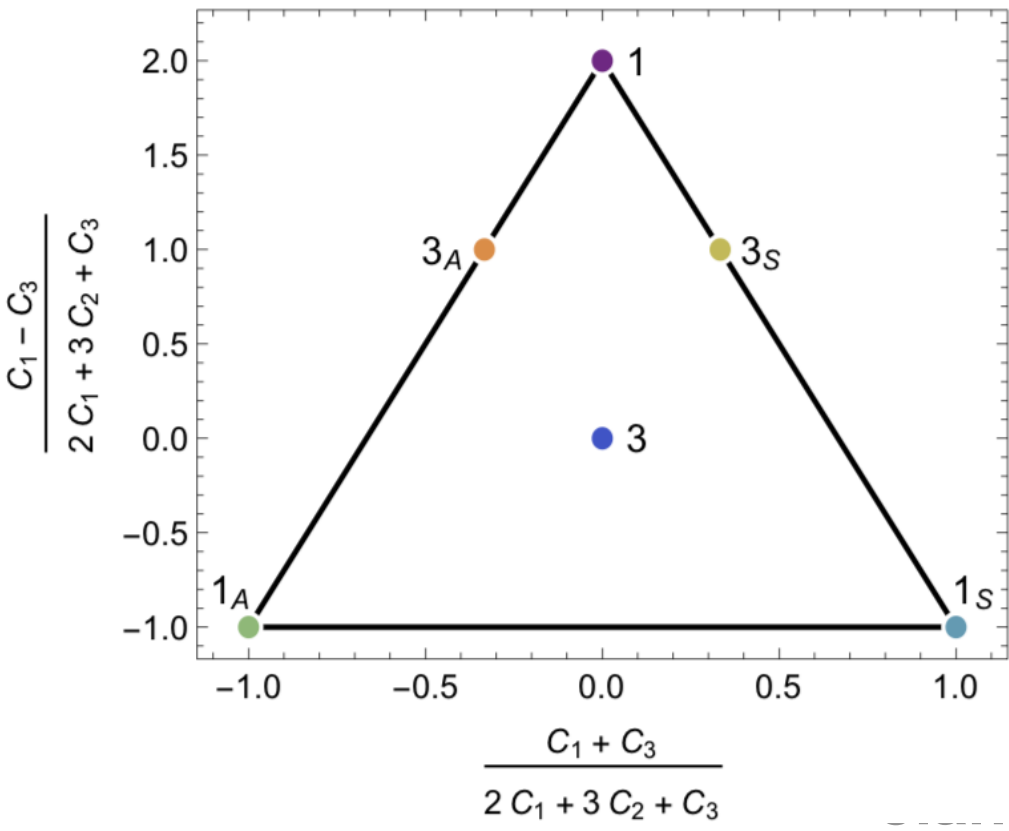
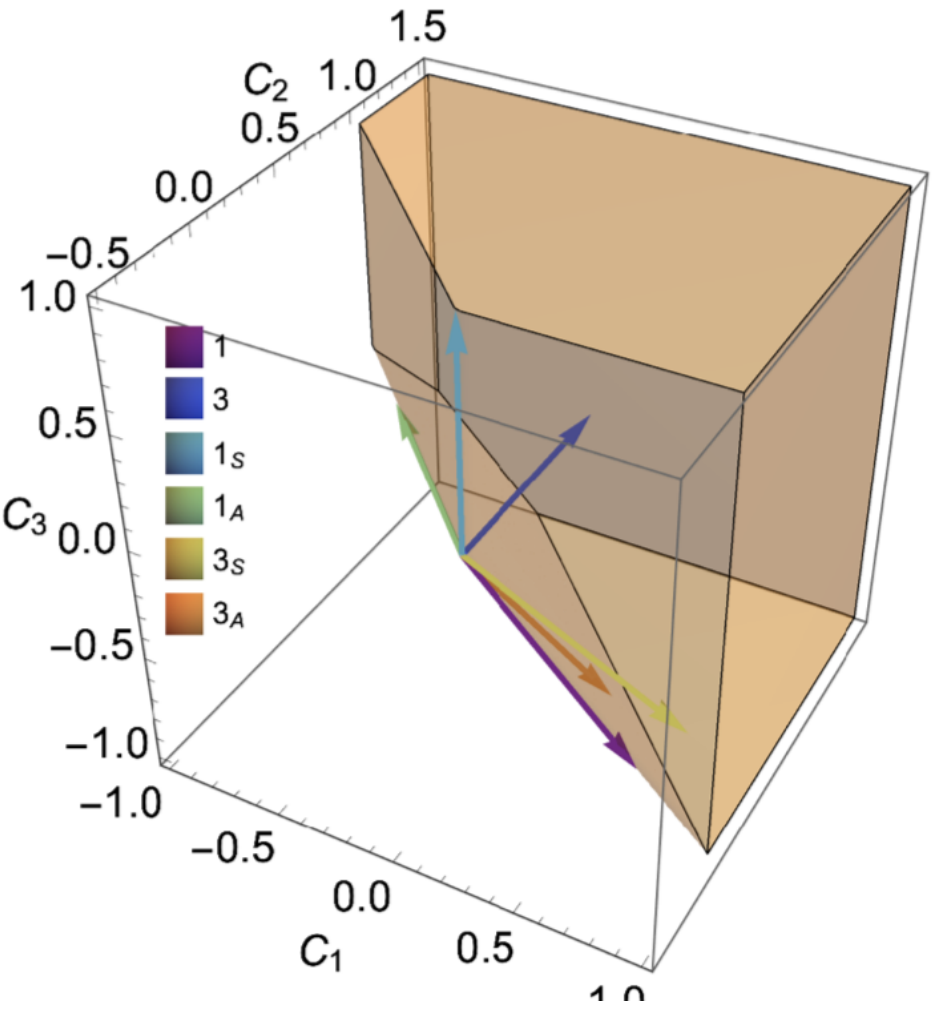
$$A(s, t) \sim \int_{\Lambda^2}^{\infty} \frac{d\mu}{\pi\mu^2} \left[\frac{s^2}{\mu - s} + \frac{u^2}{\mu - u} \right] \text{Im } A(\mu, t)$$

EFT amplitude

IR ~ UV connection

UV full amplitude

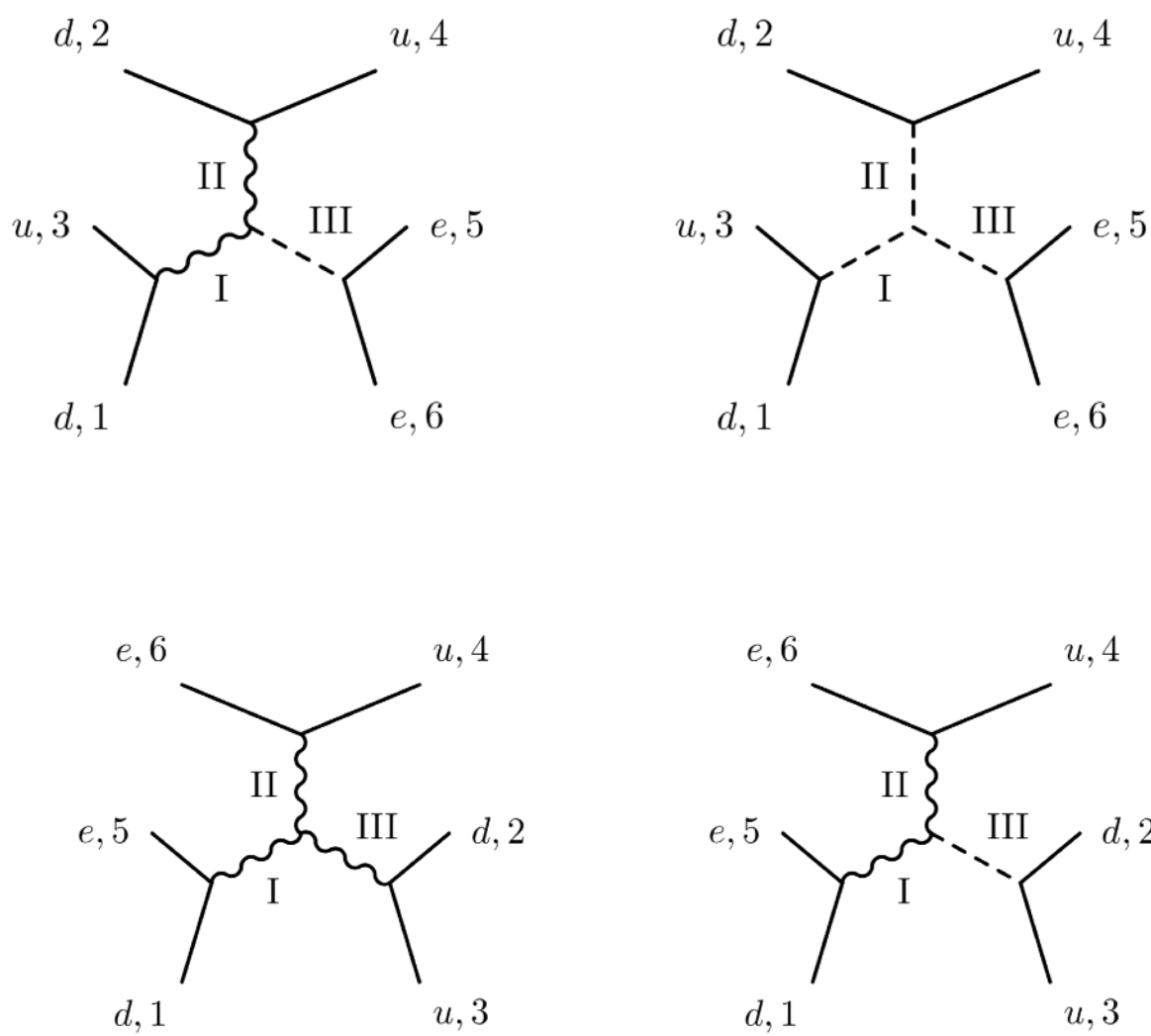
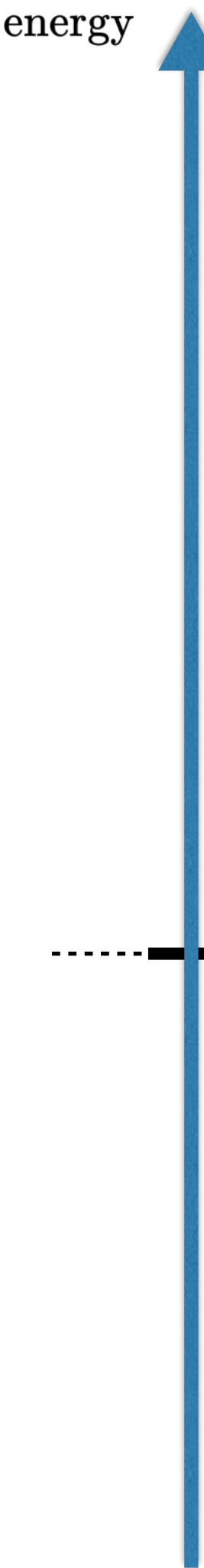
$$\text{Disc } A_{ij \rightarrow kl}(s) = A_{ij \rightarrow kl}(s) - A_{kl \rightarrow ij}(s)^* = i \sum_X M_{ij \rightarrow X}(s) M_{kl \rightarrow X}(s)^*$$



Complete dim-9 UV for $0\nu bb$

Complementary searches among LHC searches, low energy precision and others

[Gui-Jun Ding, Cai-Chang Li, Shun Zhou, Gang Li, J.-H. Yu...]

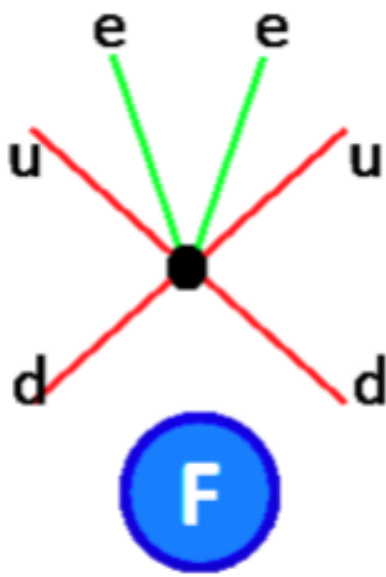


$(\mathbf{r}_i, J_i)$	$(1, 1, 0)$	$(0, 0, 0)$
$(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_3)$	$\frac{4}{3}\mathcal{O}_1 + 2\mathcal{O}_2$	$-\frac{2}{3}\mathcal{O}_2$
$(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_1)$	$-2\mathcal{O}_2$	$\frac{4}{3}\mathcal{O}_1 + \frac{2}{3}\mathcal{O}_2$
$(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_3)$	$-4\mathcal{O}_1 - 6\mathcal{O}_2$	$2\mathcal{O}_2$
$(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_1)$	$6\mathcal{O}_2$	$-4\mathcal{O}_1 - 2\mathcal{O}_2$

$(\mathbf{r}_i, J_i)$	$(1, 1, 1)$	$(1, 1, 0)$
$(\mathbf{3}_3, \mathbf{8}_2, \mathbf{\bar{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	$\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$
$(\mathbf{3}_1, \mathbf{8}_2, \mathbf{\bar{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	0
$(\mathbf{3}_3, \mathbf{1}_2, \mathbf{\bar{3}}_2)$	$-\frac{4}{3}\mathcal{O}_1$	$\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$
$(\mathbf{3}_1, \mathbf{1}_2, \mathbf{\bar{3}}_2)$	$-\frac{4}{3}\mathcal{O}_1$	0

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, J.H.Yu, Xiao-Long Zheng, 2603.19358]

[Gang Li, J.H.Yu, X. Zhao, 2311.15422]



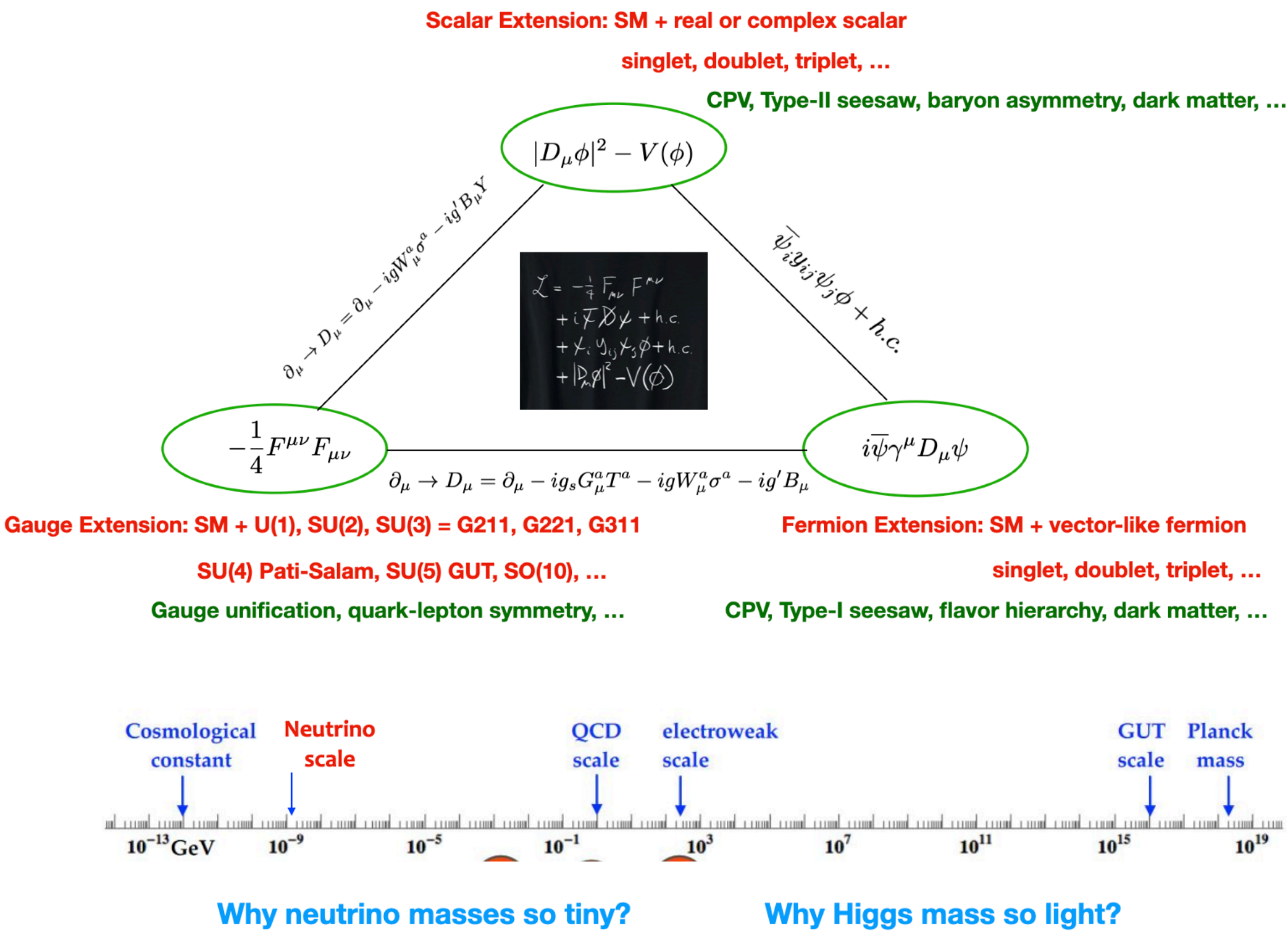
$$\mathcal{O}_1 = \frac{1}{4}(L_u^\dagger{}^j L_v^\dagger{}^i)(Q_{p_{ai}} Q_{r_{bj}})(u_{cs}{}^b u_{ct}{}^a)$$

$$\mathcal{O}_2 = -\frac{1}{4}(L_u^\dagger{}^j L_v^\dagger{}^i)(Q_{p_{ai}} u_{cs}{}^b)(Q_{r_{bj}} u_{ct}{}^a).$$

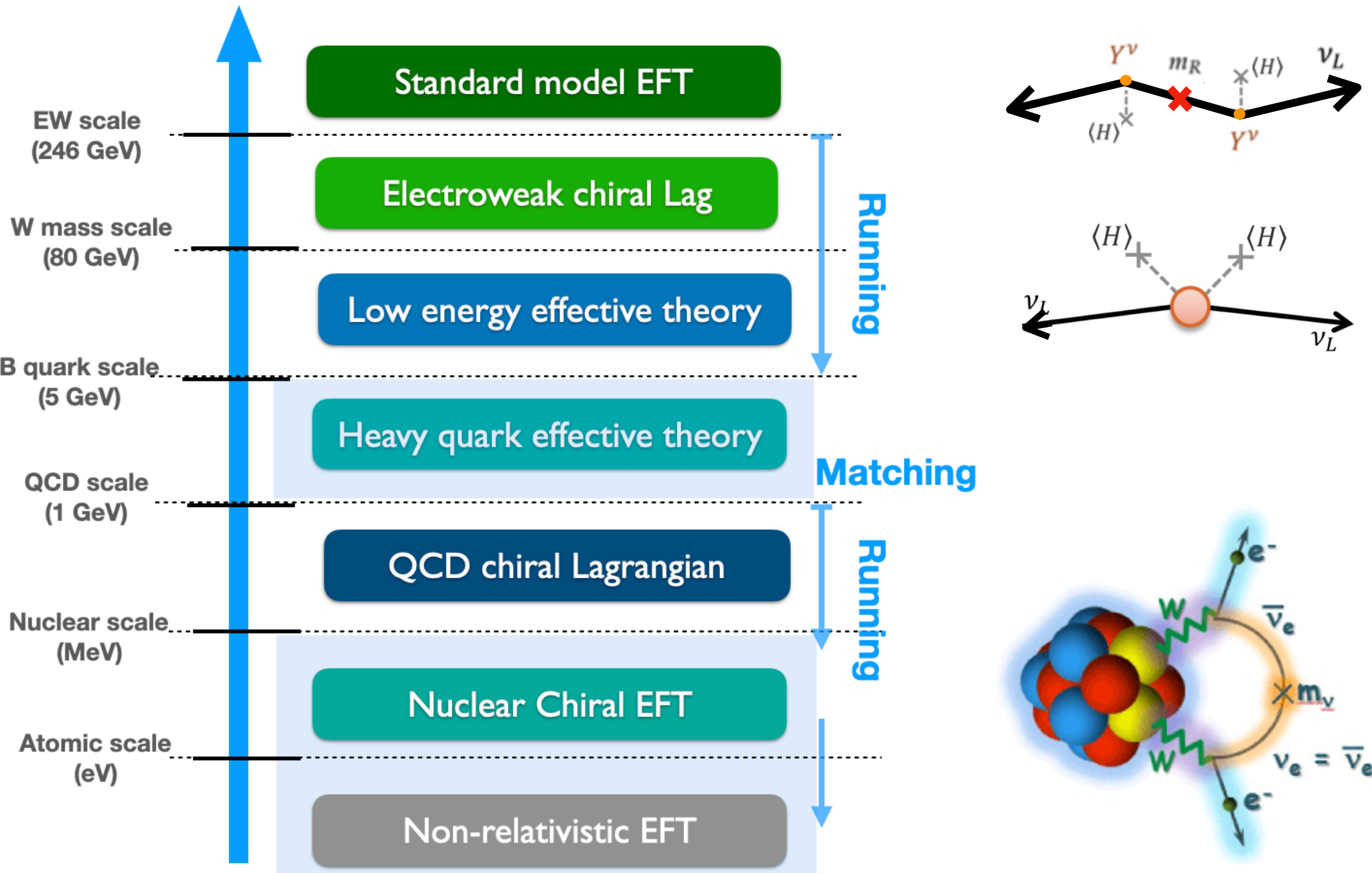
Summary and Outlook

Summary

Top-down: New physics model building



Bottom-up: New physics from EFT



Outlook

EFT motivated 47 Resonances search at future colliders, and complementary search at low energy

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\mathcal{D} \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3}$$

Tree-level origin of all dim-5/6/7 operators

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Scalars

Notation	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{1})_2$	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{1}, \mathbf{3})_1$	$(\mathbf{1}, \mathbf{4})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{4})_{\frac{3}{2}}$

Notation	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
Name	ω_4	ω_1	ω_2	Π_1	Π_7	ζ
Irrep	$(\mathbf{3}, \mathbf{1})_{-\frac{4}{3}}$	$(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}, \mathbf{3})_{-\frac{1}{3}}$

Notation	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}
Name	Ω_2	Ω_1	Ω_4	Υ_1	Φ
Irrep	$(\mathbf{6}, \mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{6}, \mathbf{1})_{\frac{1}{3}}$	$(\mathbf{6}, \mathbf{1})_{\frac{4}{3}}$	$(\mathbf{6}, \mathbf{3})_{\frac{1}{3}}$	$(\mathbf{8}, \mathbf{2})_{\frac{1}{2}}$

14
Fermions

Notation	F_1	F_2	F_3	F_4	F_5	F_6	F_7
Name	N	E^c	Δ_1^c	Δ_3^c	Σ	Σ_1^c	
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{1}, \mathbf{3})_1$	$(\mathbf{1}, \mathbf{4})_{\frac{1}{2}}$
Notation	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	F_{14}
Name	D	U	Q_5	Q_1	Q_7	T_1	T_2
Irrep	$(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}, \mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3}, \mathbf{3})_{\frac{2}{3}}$

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Vectors

Notation	V_1	V_2	V_3	V_4	V_5	V_6	V_7
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{L}_3^\dagger$	$\mathcal{W}$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_5$
Irrep	$(\mathbf{1}, \mathbf{1})_0$	$(\mathbf{1}, \mathbf{1})_1$	$(\mathbf{1}, \mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1}, \mathbf{3})_0$	$(\mathbf{3}, \mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}, \mathbf{1})_{\frac{5}{3}}$	$(\mathbf{3}, \mathbf{2})_{-\frac{5}{6}}$
Notation	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}
Name	$\mathcal{Q}_1$	$\mathcal{X}$	$\mathcal{Y}_1^\dagger$	$\mathcal{Y}_5^\dagger$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$
Irrep	$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}, \mathbf{3})_{\frac{2}{3}}$	$(\mathbf{6}, \mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{6}, \mathbf{2})_{\frac{5}{6}}$	$(\mathbf{8}, \mathbf{1})_0$	$(\mathbf{8}, \mathbf{1})_1$	$(\mathbf{8}, \mathbf{3})_0$

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

[Xu-Xiang Li, Zhe Ren, **J.H.Yu**, 2307.10380]

Outlook



[Weinberg 1933.5.3 - 2021.7.23]

The Making of the Standard Model

Steven Weinberg*

Well, those were great days. The 1960s and 1970s were a time when experimentalists and theorists were really interested in what each other had to say, and made great discoveries through their mutual interchange. We have not seen such great days in elementary particle physics since that time, but I expect that we will see good times return again in a few years, with the beginning of a new generation of experiments at this laboratory.

Thanks very much for your attention!