Institute of Theoretical Physics
Chinese Academy of Sciences

Physics Beyond the Standard Model

Jiang-Hao Yu (于江浩)

Institute of Theoretical Physics, Chinese Academy of Sciences

第五届量子场论及其应用研讨会

Nov. 1, 2025 @ 北京

Outline

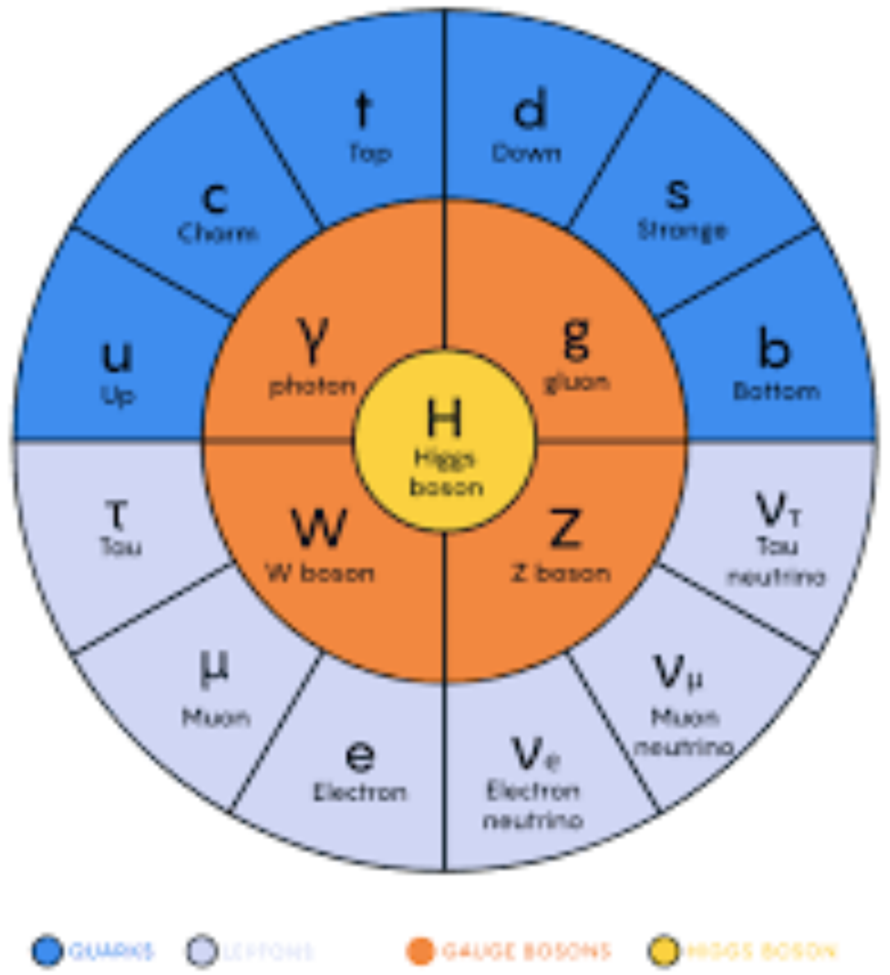
- Motivation for new physics
- New physics model building: top-down approach
- New physics from EFT: bottom-up approach
- New way of searching new physics
- Summary and outlook

Too broad topic
Apologize for many missing references …

Motivation for new physics

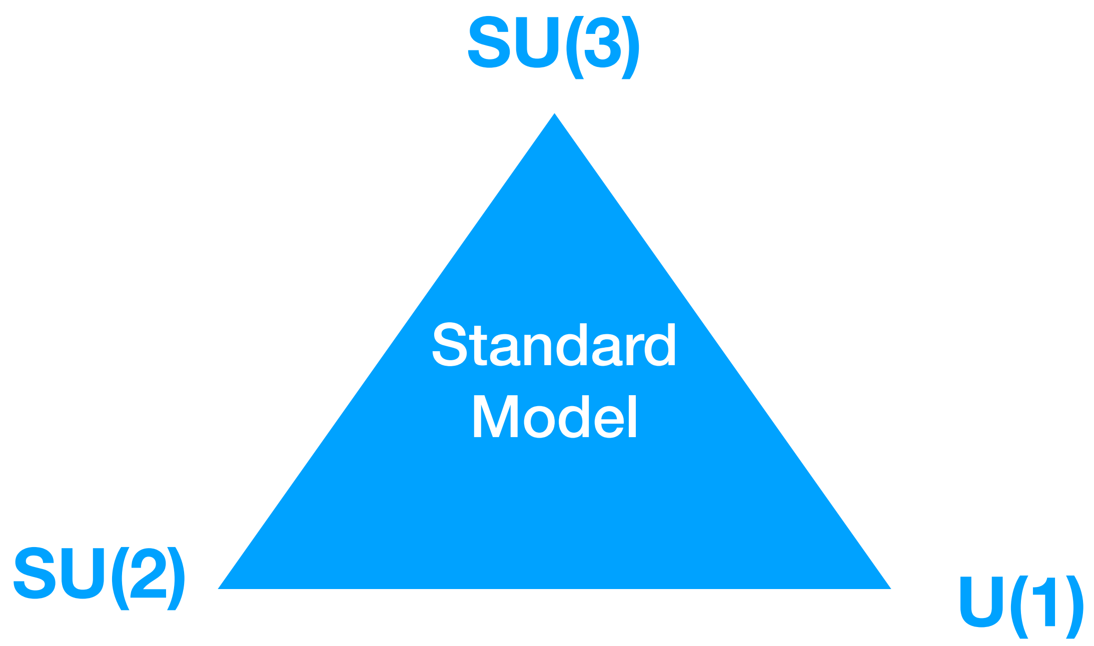
Standard model of particle physics

17 elementary particles



All discovered

3 kinds of interactions



All found, also

EW SSB verified

4 (EW) + 2 (QCD) + 13 (flavor) + 9 (v) = 28 parameters

(α_s, θ)

$$
\begin{aligned}
\mathcal{L}_{SM} = & \underbrace{-\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\text{kinetic energies and self-interactions of the gauge bosons}} - \theta\frac{\alpha_s}{8\pi}G^{\mu\nu}_{a}\tilde{G}^{a}_{\mu\nu} \\
& + \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
& + \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}} \\
& + \underbrace{g''(\bar{q}\gamma^{\mu}T_{a}q)G^{a}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}
\end{aligned}
$$

$17+9 =$	1	1	1	1	$9+3$	4	6
formal:	g	g'	v	λ	λ_f	$\mathbf{V}_{\rm CKM}$	$\mathrm{U}_{\rm PMNS}$
practical:	α	M_W	M_Z	M_H	m_f		

23 = 4 + 1 + 13 + 5 measured but 5 unknown

Absolute nv mass, 3 CPV phases

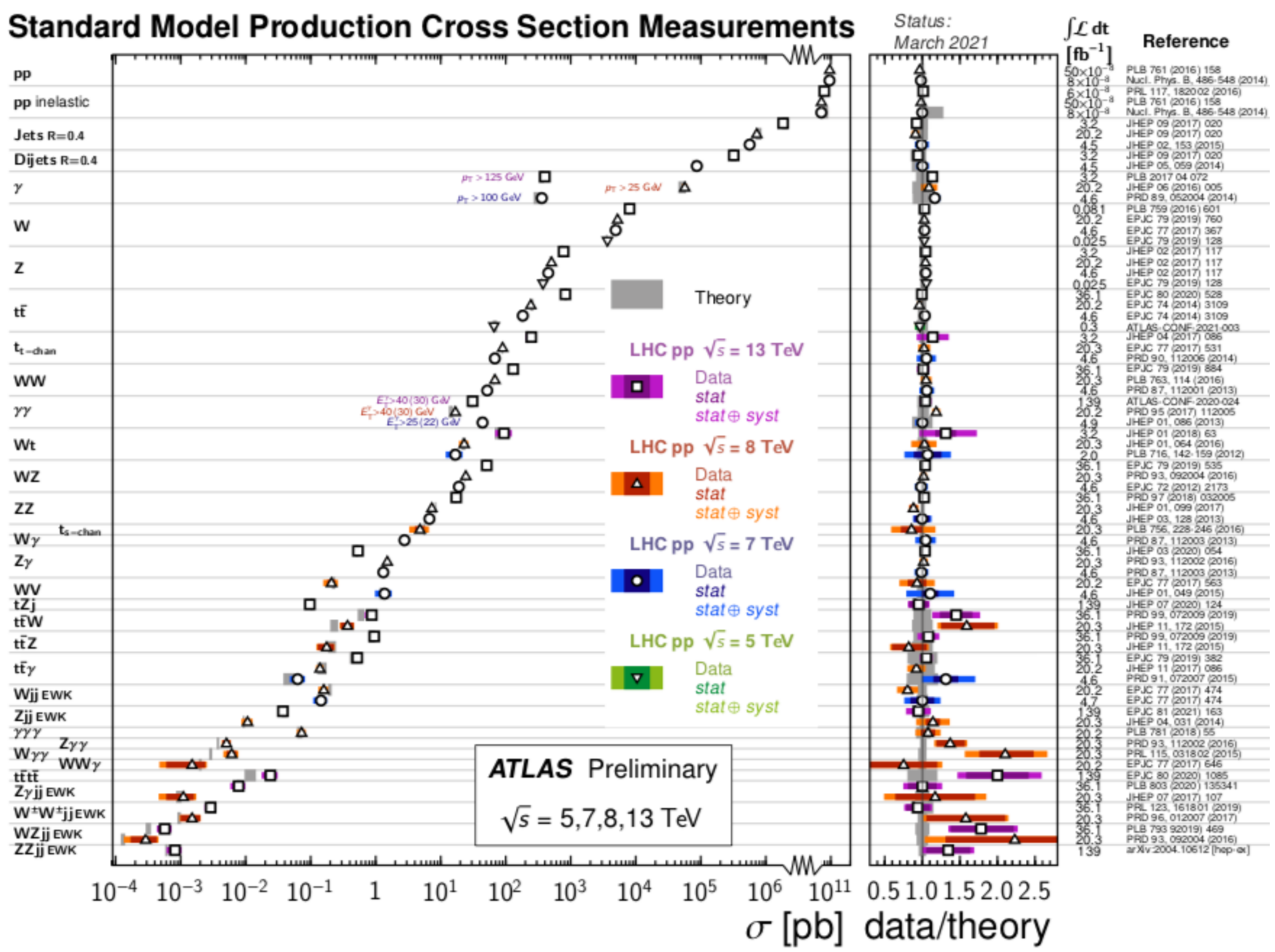
$$
\begin{array}{cccc}
\theta_{23}\ \&\ \Delta M^2_{32} & \text{CP phase } \delta\ \&\ \theta_{13} & \theta_{12}\ \&\ \Delta M^2_{21} & \text{Majorana phase} \\
\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} &
\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} &
\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} &
\begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}
\end{array}
$$

[Shun Zhou's talk]

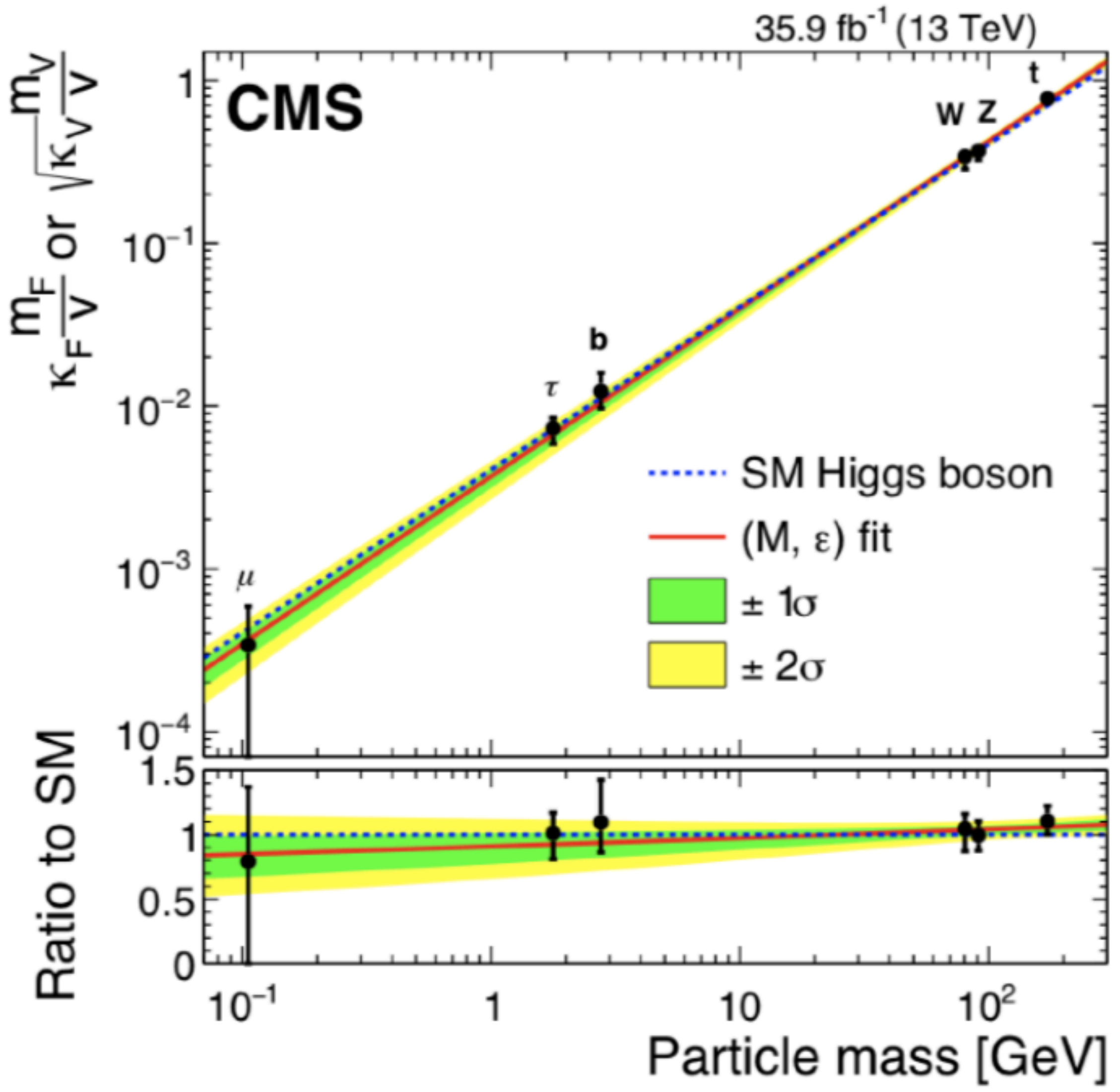
Note that $\theta_B B_{\mu\nu}\tilde{B}_{\mu\nu}$ is not physical, while $\theta_W W^k_{\mu\nu}\tilde{W}^k_{\mu\nu}$ can be eliminated by chiral rotation

Theoretical and experimental status

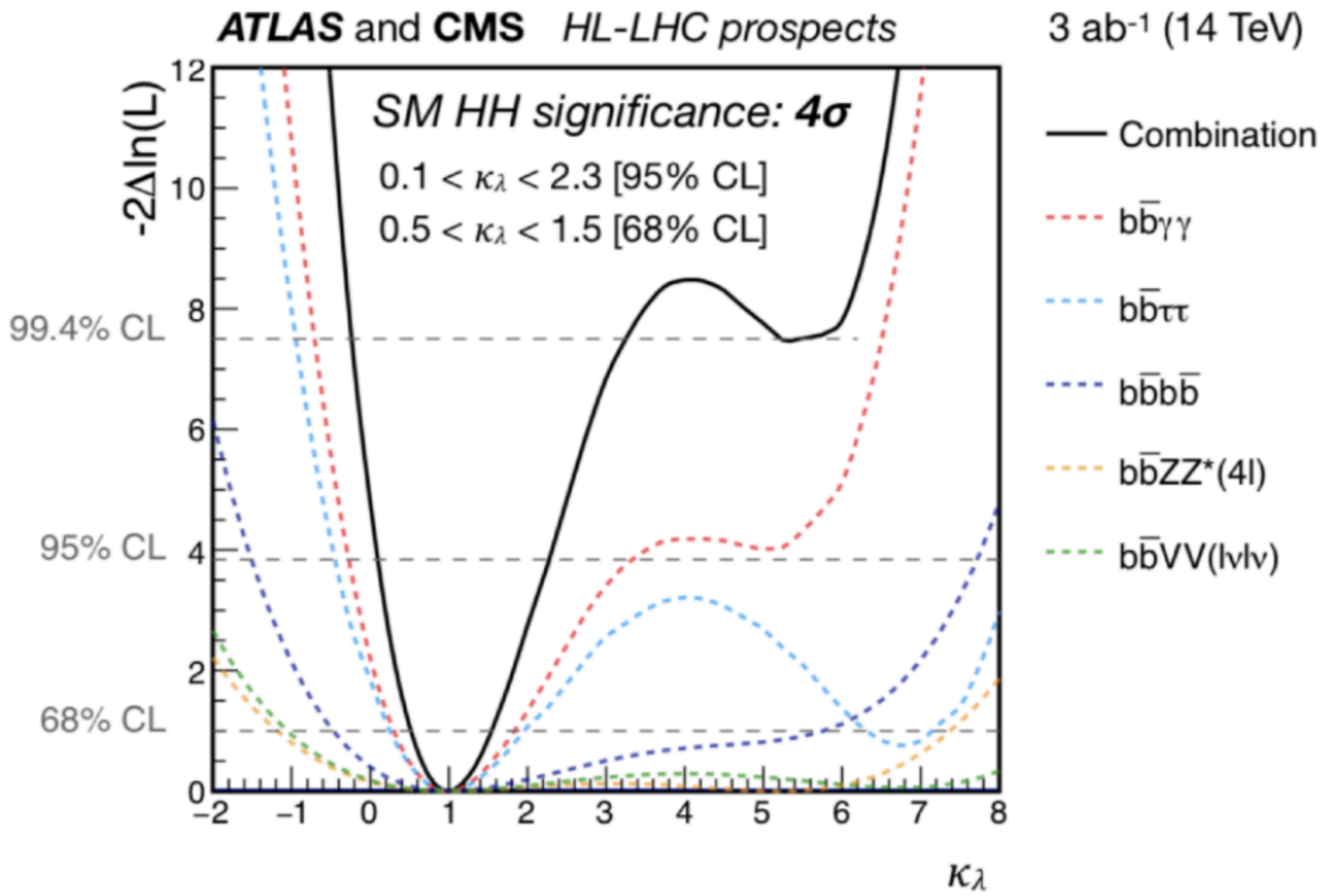
Validate higher order SM predictions



light flavor Higgs coupling?



Higgs self coupling?



Top quark pair production at small transverse momentum in hadronic collisions #10

Hai Tao Li (Peking U., SKLNPT), Chong Sheng Li (Peking U., SKLNPT and Peking U., CHEP), Ding Yu Shao (Peking U., SKLNPT), Li Lin Yang (Peking U., SKLNPT and Peking U., CHEP), Hua Xing Zhu (SLAC) (Jul 9, 2013)

Published in: *Phys.Rev.D* 88 (2013) 074004 • e-Print: 1307.2464 [hep-ph]

pdf DOI cite claim reference search 101 citations

Transverse-momentum resummation for top-quark pairs at hadron colliders #11

Hua Xing Zhu (Peking U.), Chong Sheng Li (Peking U. and Peking U., CHEP), Hai Tao Li (Peking U.), Ding Yu Shao (Peking U.), Li Lin Yang (Zurich U.) (Aug, 2012)

Published in: *Phys.Rev.Lett.* 110 (2013) 8, 082001 • e-Print: 1208.5774 [hep-ph]

pdf DOI cite claim reference search 101 citations

Improved Resummation Prediction on Higgs Production at Hadron Colliders #1

Jian Wang (Peking U.), Chong Sheng Li (Peking U. and Peking U., CHEP), Zhao Li (Michigan State U.), C.P. Yuan (Michigan State U. and Peking U., CHEP), Hai Tao Li (Peking U.) (May, 2012)

Published in: *Phys.Rev.D* 86 (2012) 094026 • e-Print: 1205.4311 [hep-ph]

pdf DOI cite claim reference search 26 citations

Threshold resummation effects in Higgs boson pair production at the LHC #3

Ding Yu Shao (Peking U.), Chong Sheng Li (Peking U. and Peking U., CHEP), Hai Tao Li (Peking U.), Jian Wang (Peking U.) (Jan, 2013)

Published in: *JHEP* 07 (2013) 169 • e-Print: 1301.1245 [hep-ph]

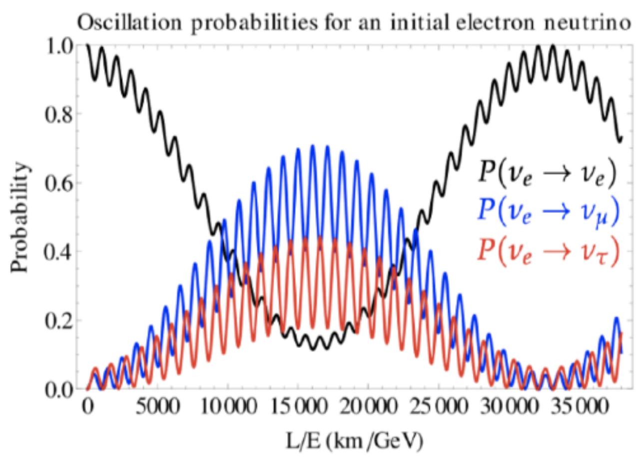
pdf DOI cite claim reference search 230 citations

Motivation for new physics

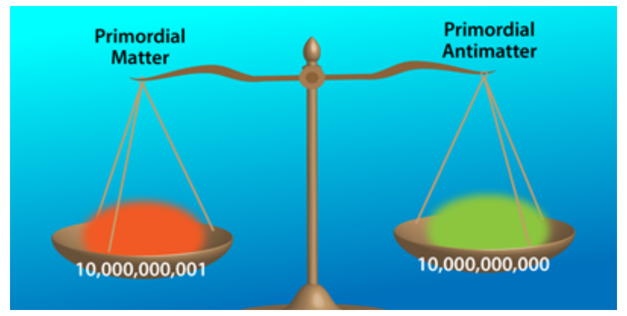
There are experimental challenges in the standard model and theoretical motivation for new physics

experimental challenges

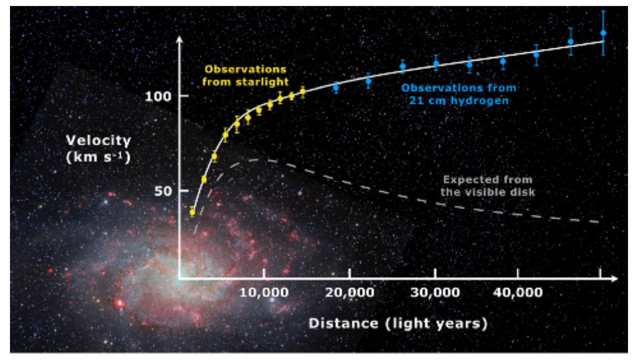
Neutrino masses



Baryon asymmetry

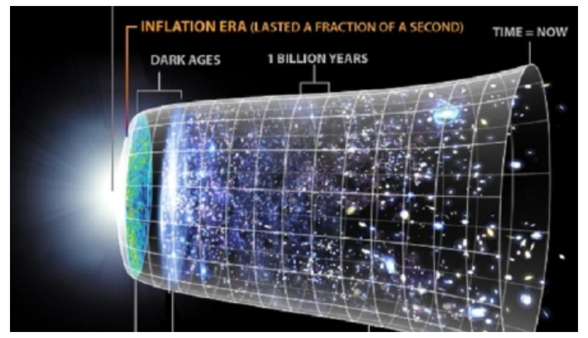


Dark matter

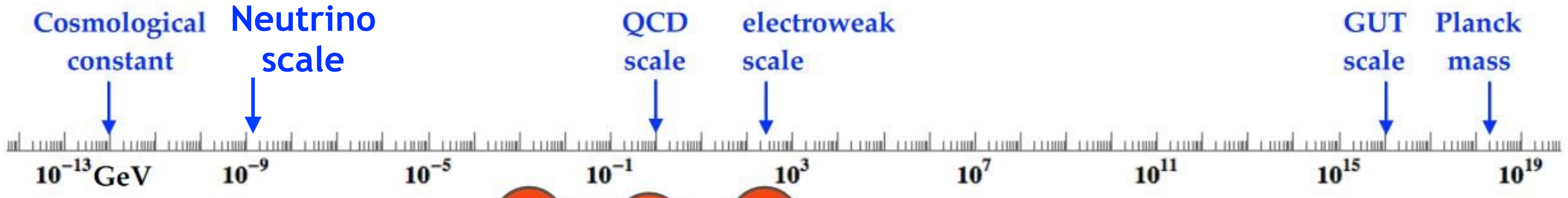


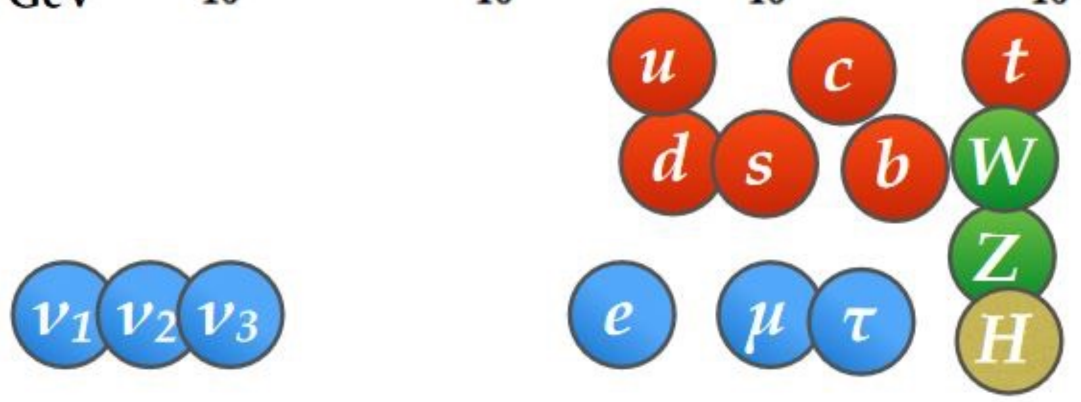
Inflation

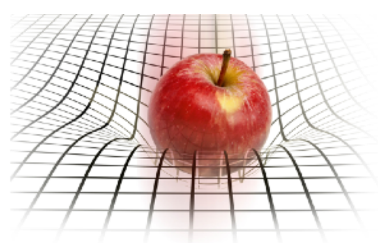
[Zhongzhi Xianyu's talk]



theoretical motivation



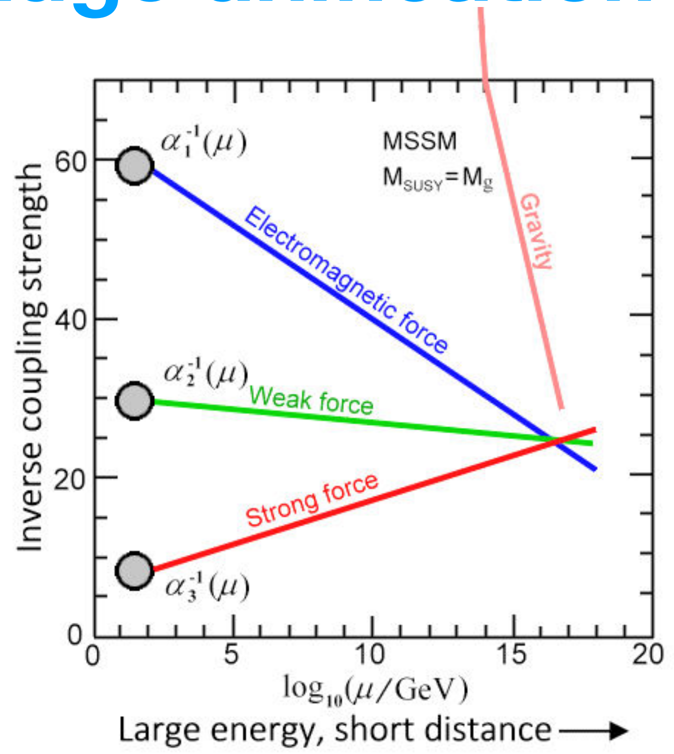




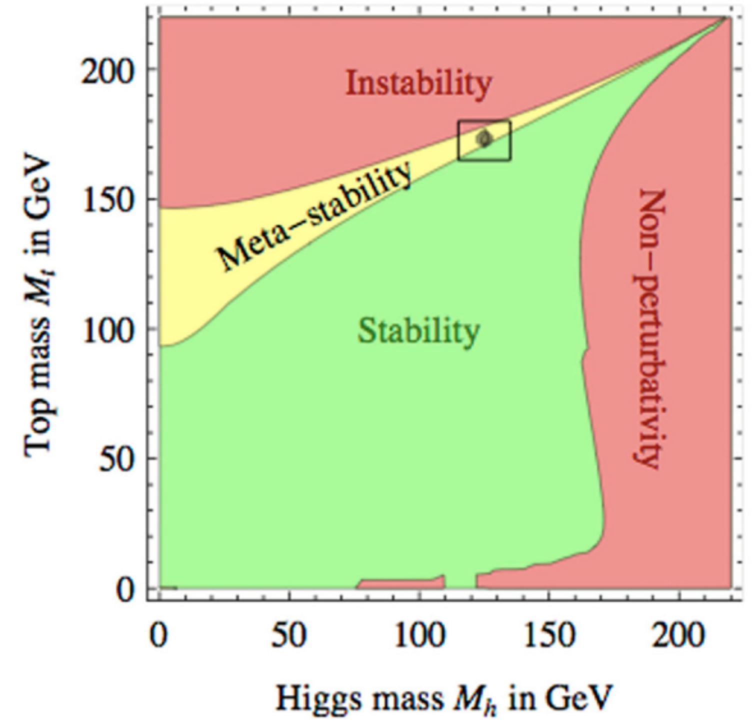
Fermion flavor hierarchy

Higgs hierarchy problem

Gauge unification



Vacuum stability



New Physics Model Building

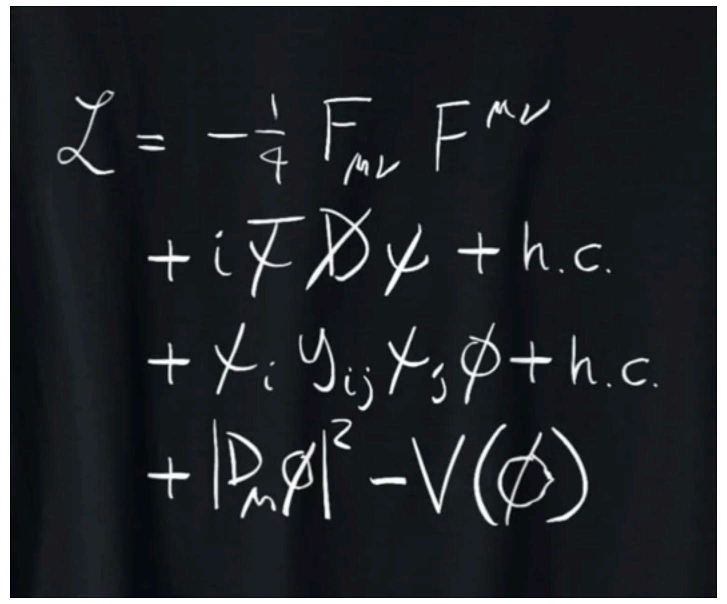
Standard model extension

Scalar sector

$$|D_\mu \phi|^2 - V(\phi)$$

$\partial_\mu \to D_\mu = \partial_\mu - igW_\mu^a \sigma^a - ig' B_\mu Y$

$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$



$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$i\bar{\psi}\gamma^\mu D_\mu \psi$$

$\partial_\mu \to D_\mu = \partial_\mu - ig_s G_\mu^a T^a - igW_\mu^a \sigma^a - ig' B_\mu$

Gauge sector

Fermion sector

Standard model extension

Scalar Extension: SM + real or complex scalar

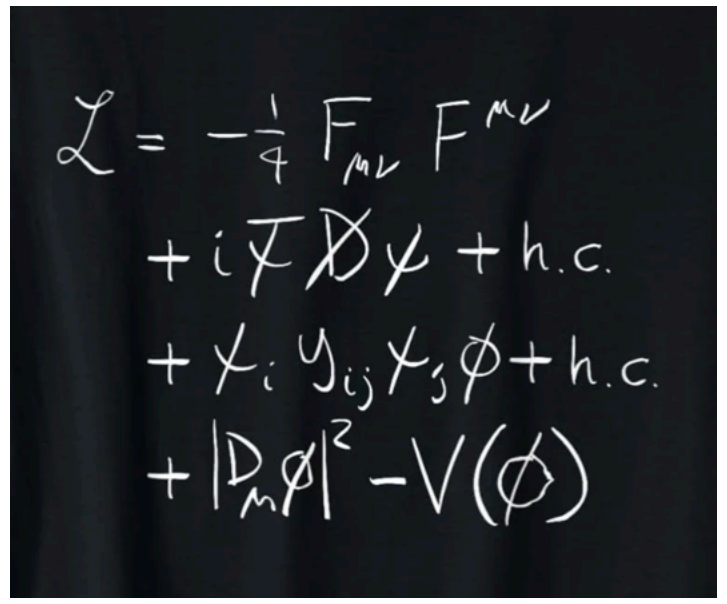
singlet, doublet, triplet, …

baryon asymmetry, CPV, Type-II seesaw, dark matter, …

$$|D_\mu \phi|^2 - V(\phi)$$

$$\partial_\mu \to D_\mu = \partial_\mu - igW^a_\mu \sigma^a - ig' B_\mu Y$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$i\bar{\psi}\gamma^\mu D_\mu \psi$$

$$\partial_\mu \to D_\mu = \partial_\mu - ig_s G^a_\mu T^a - igW^a_\mu \sigma^a - ig' B_\mu$$

Gauge Extension: SM + U(1), SU(2), SU(3) = G211, G221, G311

SU(4) Pati-Salam, SU(5) GUT, SO(10), …

Gauge unification, quark-lepton symmetry, …

Fermion Extension: SM + vector-like fermion

singlet, doublet, triplet, …

Type-I seesaw, flavor hierarchy, CPV, dark matter, …

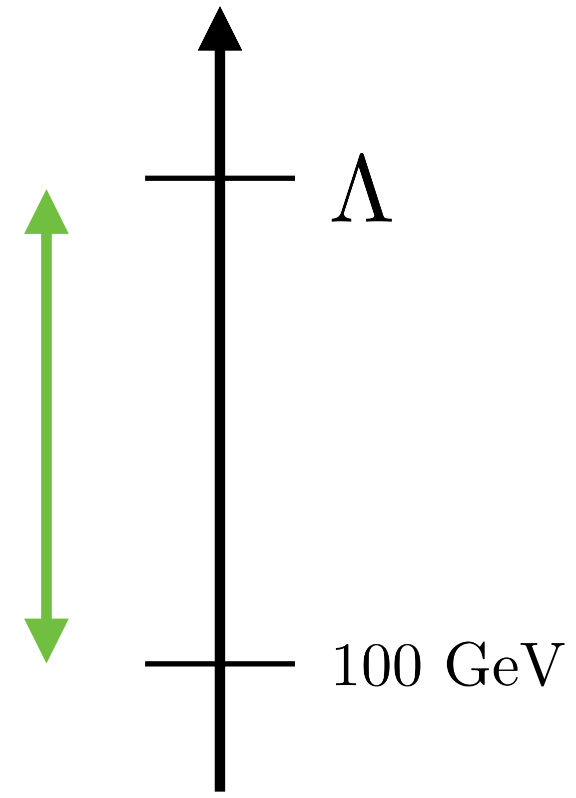
Usually additional scalar, fermion

Hierarchy problem

In extension models, new physics scale = seesaw, flavor, gauge unification scale

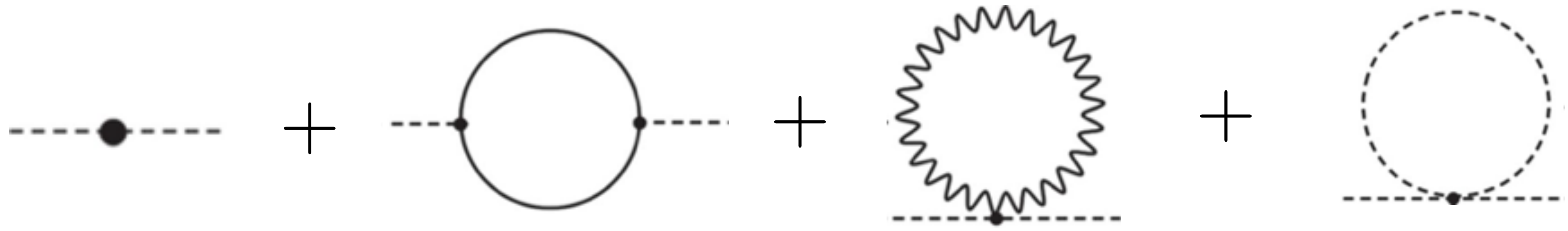
Usually solve one or two problems introduced in motivation

If new physics scale much higher than the electroweak scale, Higgs mass receives threshold corrections



Higgs mass parameter

$$-(100\ \text{GeV})^2 =$$



$$= c\,\Lambda^2 + \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{3}{4}(3g^2 + g'^2) + 6\lambda\right)$$

$$\begin{aligned} -(100\ \text{GeV})^2 = &+ 361278909847893073945209328789289{\color{red}07398}\ \text{GeV}^2 \\ &- 361278909847893073945209328789289{\color{red}17398}\ \text{GeV}^2 \end{aligned}$$

Huge fine tuning

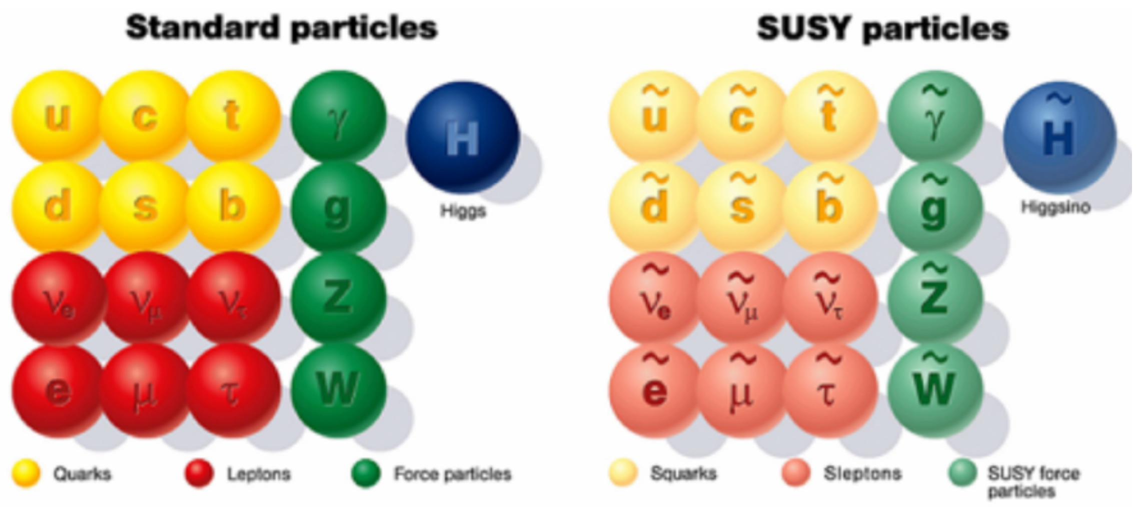
Extension models cannot solve hierarchy problem

Beyond simplified model

Introduce new physics for the Higgs boson

Supersymmetry

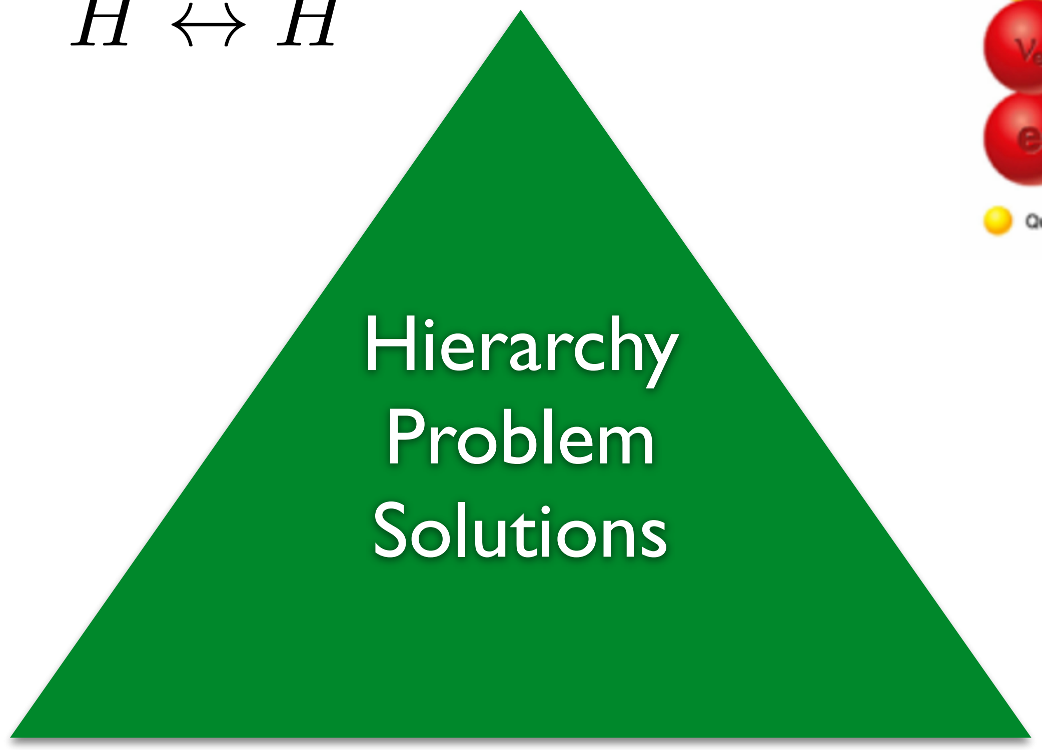
$H \leftrightarrow \tilde{H}$



Higgs Higgsino

MSSM, NMSSM,
vMSSM, TMSSM, …

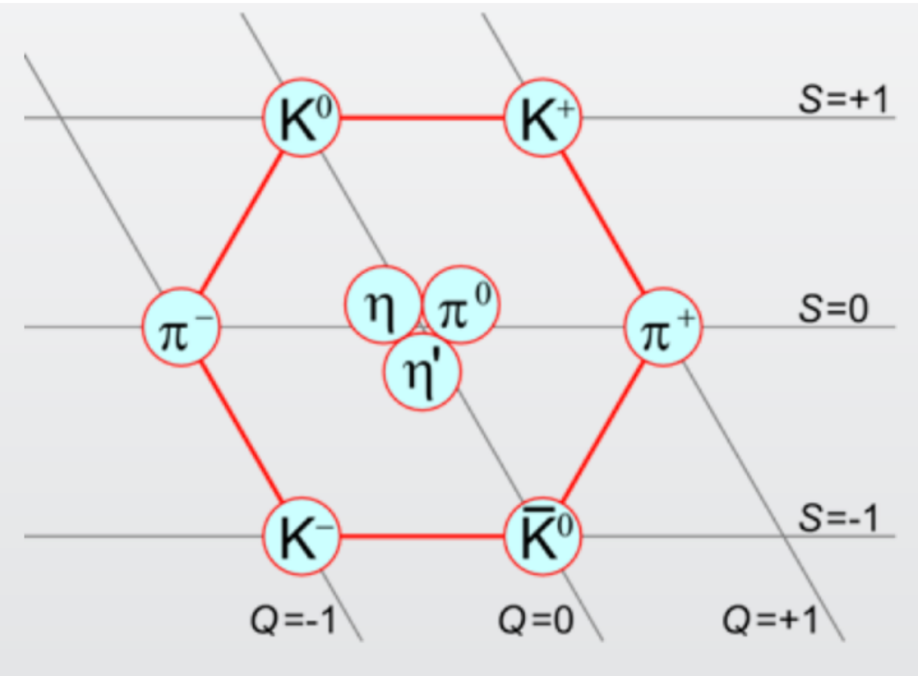
Gravity mediation
Gauge mediation
Anomaly mediation
…



Composite Higgs

shift: $h \to h + a$

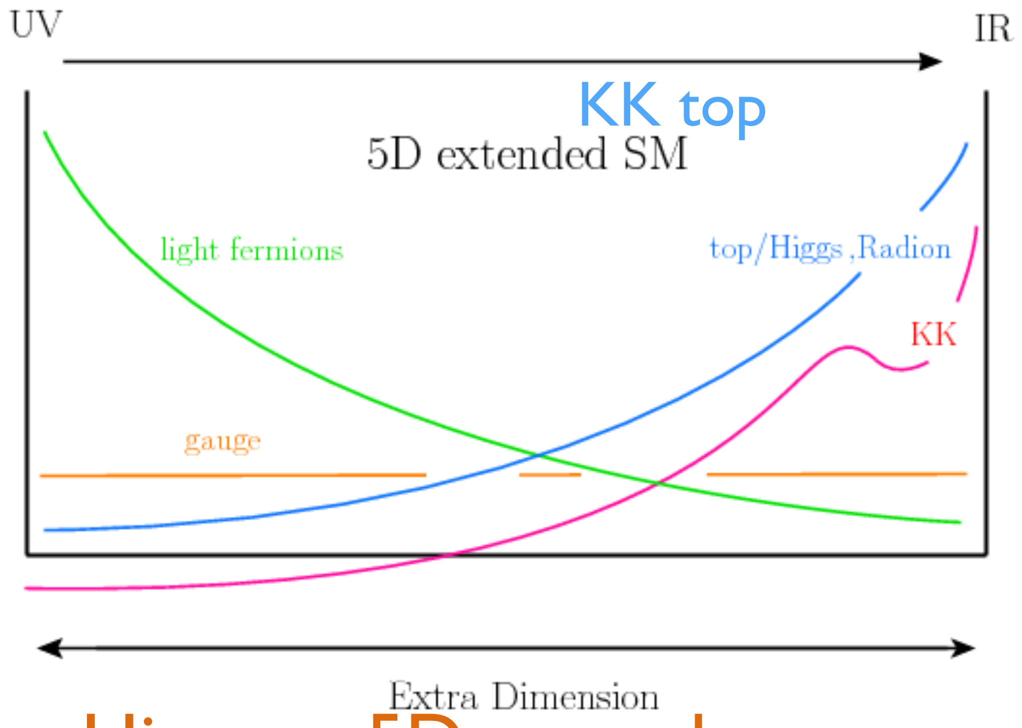
Technicolor
Little Higgs
Minimal Composite Higgs
Twin Higgs
Neutral naturalness
…



Higgs similar to pion

Extra Dimension

Conformal: $h \to e^{\omega} h$



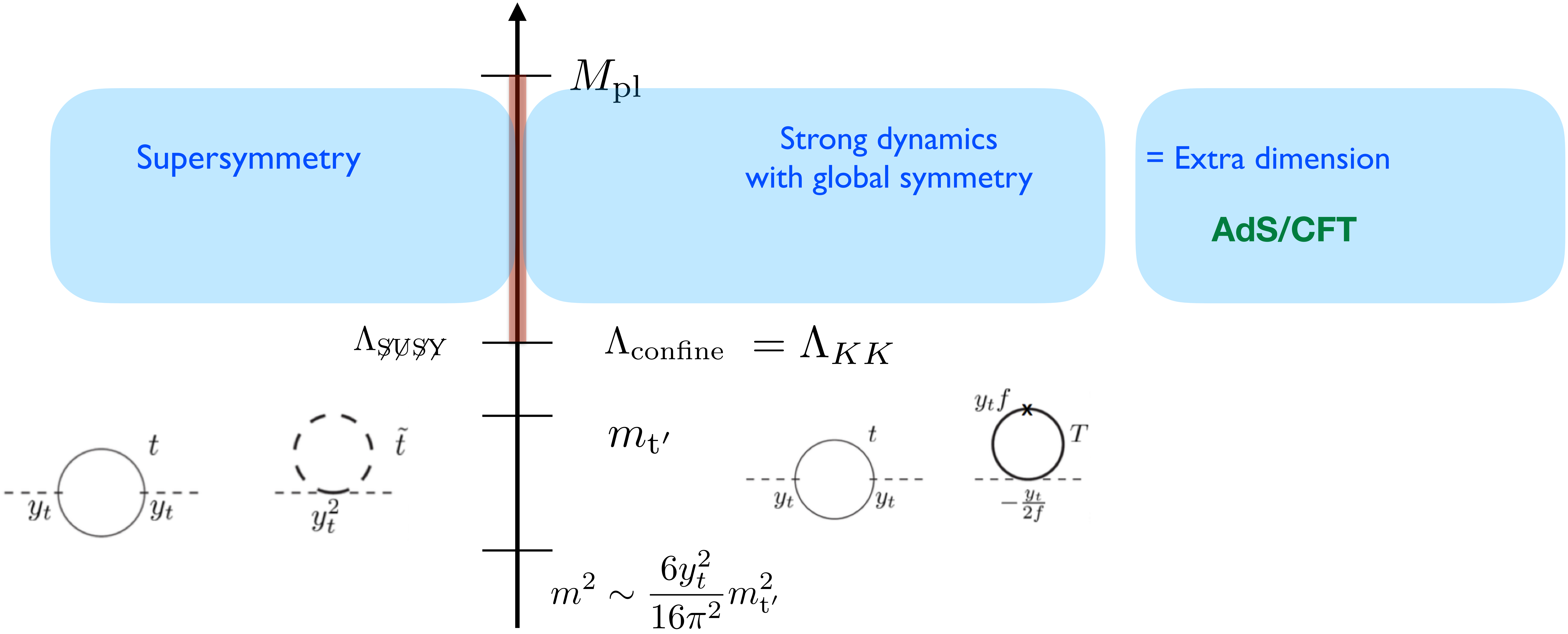
Higgs as 5D gauge boson

ADD model
Randall-Sundrum
Higgsless
Soft-wall
Flavor XD
…

Light top partner

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

Due to symmetry, effective new physics scale is much lower than Planck scale



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

Gauge unification,
baryon asymmetry,
WIMP dark matter …

Flavor hierarchy,
baryon asymmetry,
WIMP dark matter …

Dark matter candidates

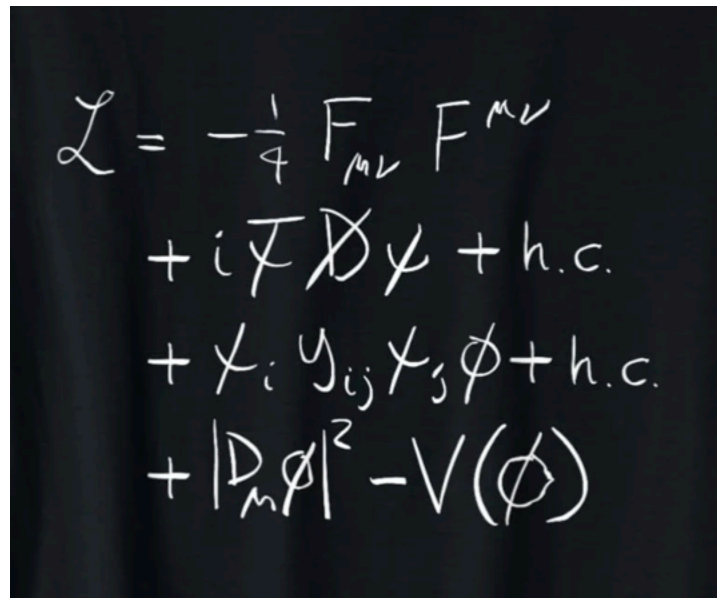
Scalar dark matter

Singlet, Axion, …

$$|D_\mu\phi|^2 - V(\phi)$$

$$\partial_\mu \to D_\mu = \partial_\mu - igW^a_\mu\sigma^a - ig'B_\mu Y$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$i\bar{\psi}\gamma^\mu D_\mu\psi$$

$$\partial_\mu \to D_\mu = \partial_\mu - ig_s G^a_\mu T^a - igW^a_\mu\sigma^a - ig'B_\mu$$

Vector dark matter

Dark photon

KK photon

Fermion dark matter

Higgsino-wino

Light sterile neutrino

Dark matter candidates

Scalar dark matter

Singlet, Axion, …

$$|D_\mu \phi|^2 - V(\phi)$$

$W^a_\mu \sigma^a - ig' B_\mu Y$

$\bar{\psi}_i y_i$

Effective Dark Matter Model: Relic density, CDMS II, Fermi LAT and LHC #2

Qing-Hong Cao (Argonne and Chicago U., EFI), Chuan-Ren Chen (Tokyo U., IPMU), Chong Sheng Li (Peking U. and Peking U., CAPT), Hao Zhang (Peking U. and Peking U., CAPT and Chicago U., EFI) (Dec, 2009)

Published in: *JHEP* 08 (2011) 018 • e-Print: 0912.4511 [hep-ph]

pdf DOI cite claim reference search 213 citations

$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$i\bar{\psi}\gamma^\mu D_\mu \psi$$

$$\partial_\mu \to D_\mu = \partial_\mu - ig_s G^a_\mu T^a - igW^a_\mu \sigma^a - ig' B_\mu$$

Vector dark matter

Dark photon

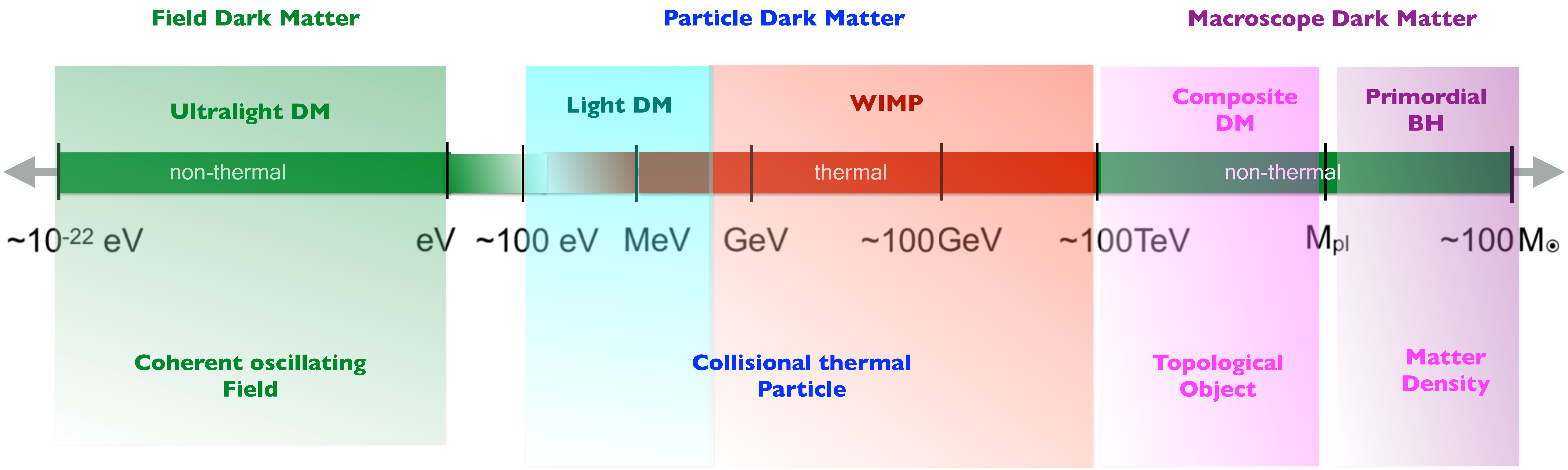
KK photon

Fermion dark matter

Higgsino-wino

Light sterile neutrino

Dark matter candidates



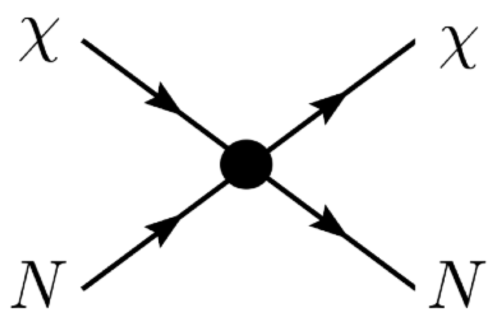
Quantum sensor detectors

Detect coherent effects of entire field
(like gravitational wave detector)

Frequency range accessible!

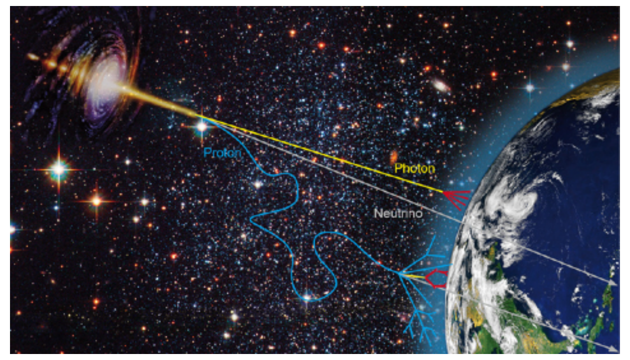
Particle detectors

Search for single, hard particle scattering



Astrophysics probes

High energy gamma-rays
Gravitational waves



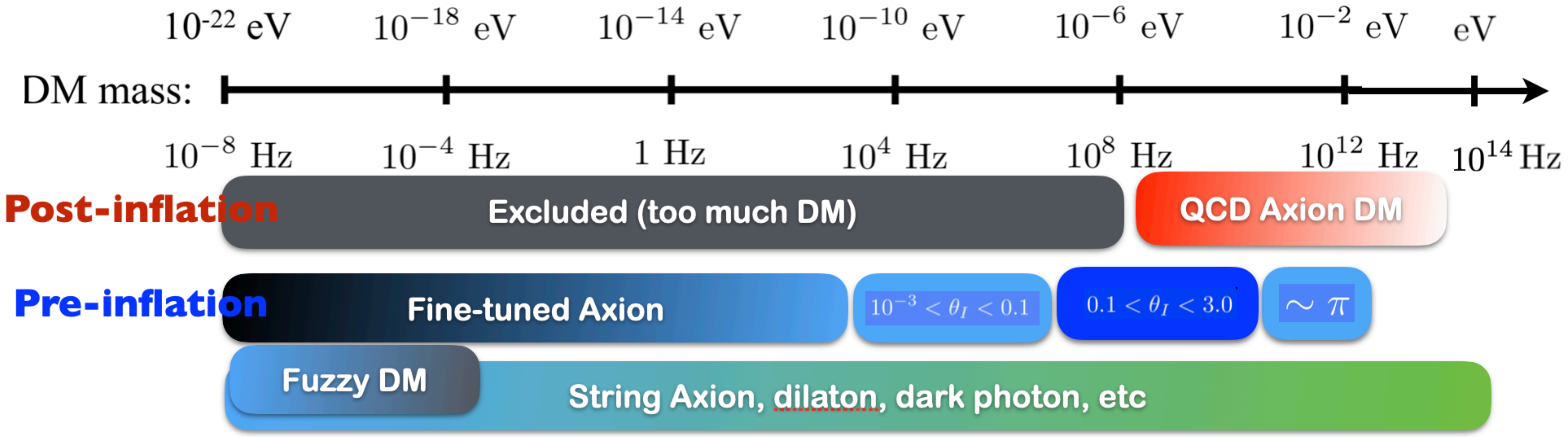
Jiang-Hao Yu (ITP-CAS)

Light new particles

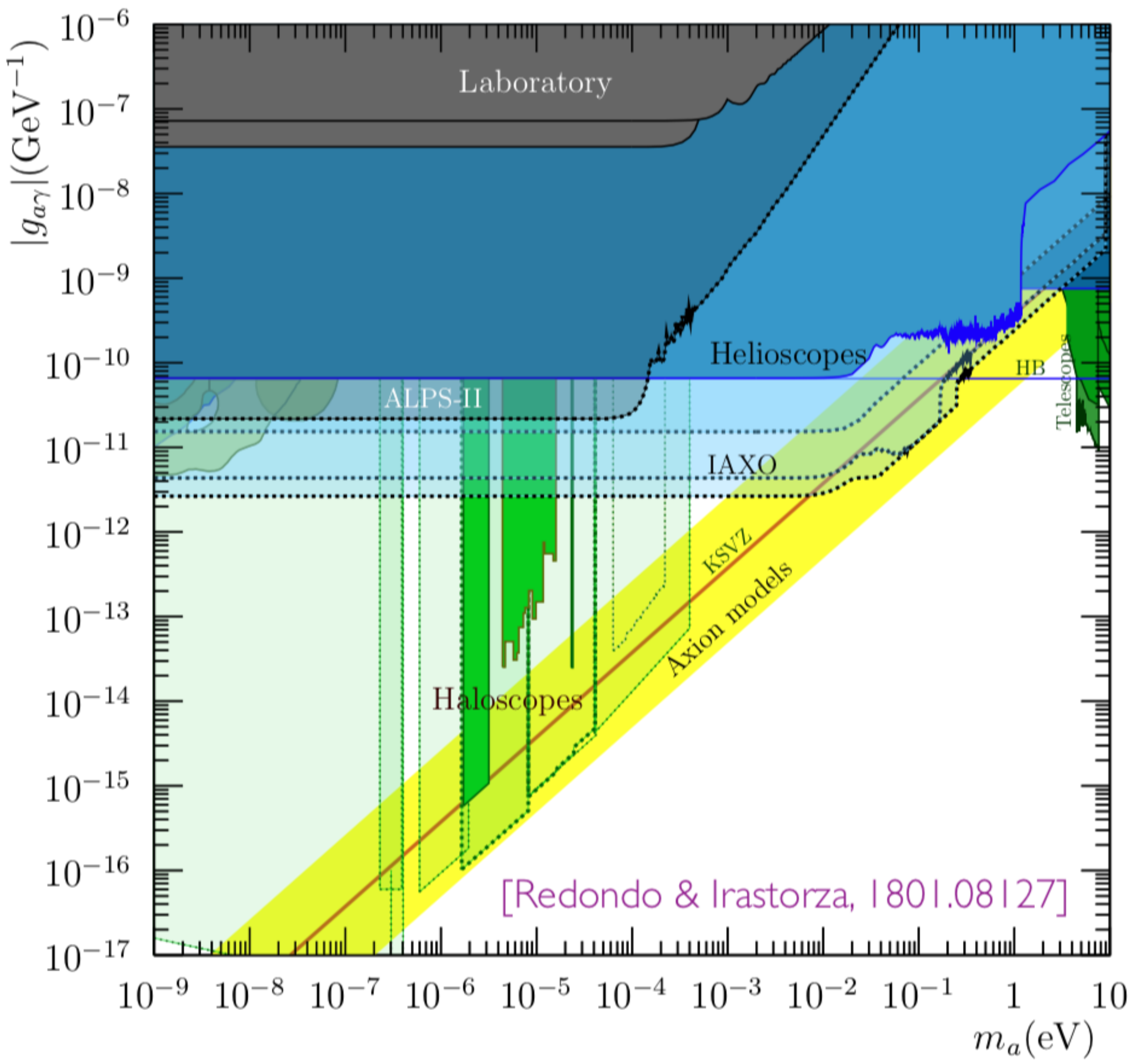
Hierarchy problem: QCD axion

$$\bar{\theta} = -\arg\det\left[e^{-i\theta} y_u y_d\right] \qquad \delta_{CKM} = \arg\det\left[y_u y_u^\dagger, y_d y_d^\dagger\right]$$

$$\bar{\theta} \lesssim 10^{-10} \qquad \delta_{\rm CKM} \simeq \mathcal{O}(1)$$

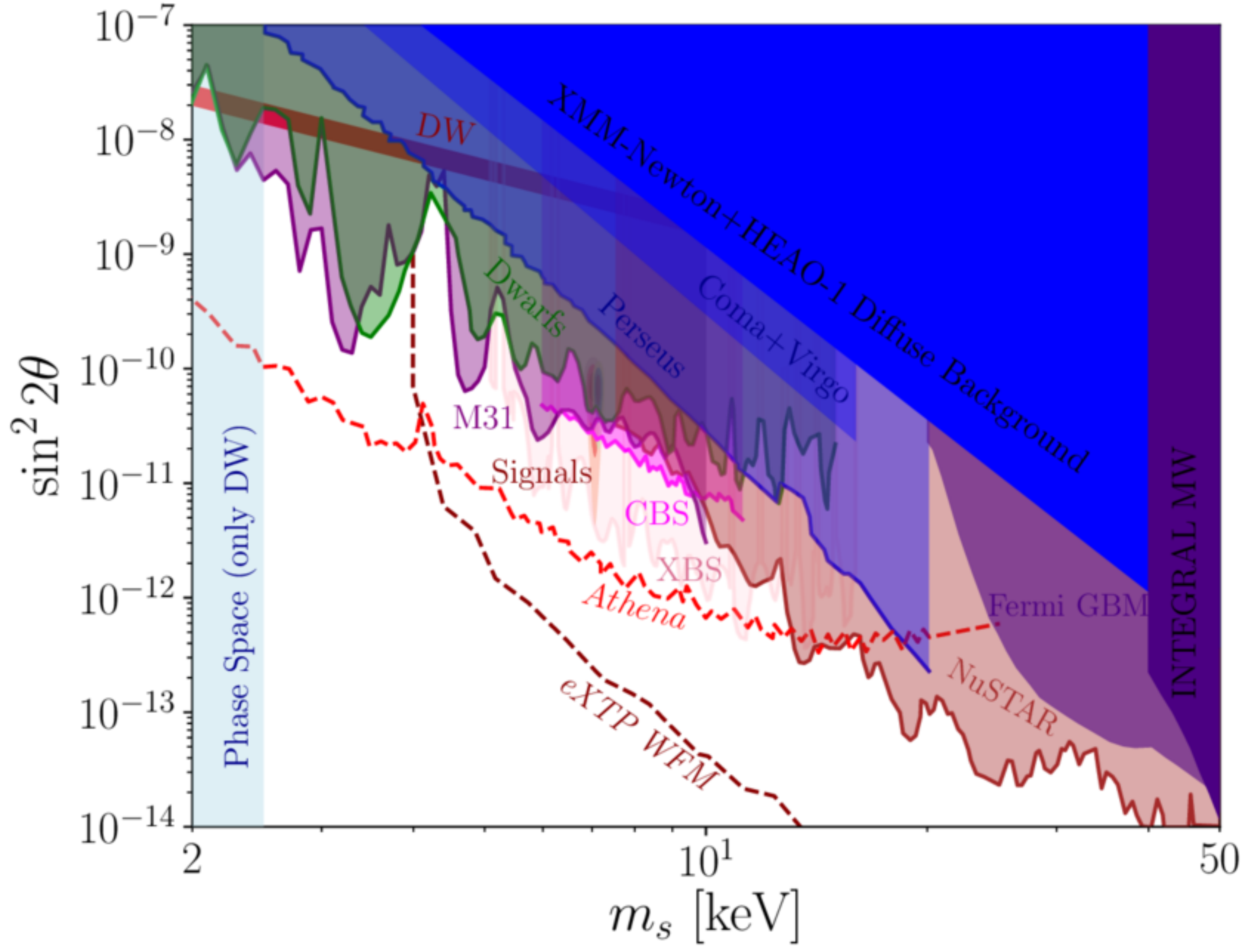


Axion search limits

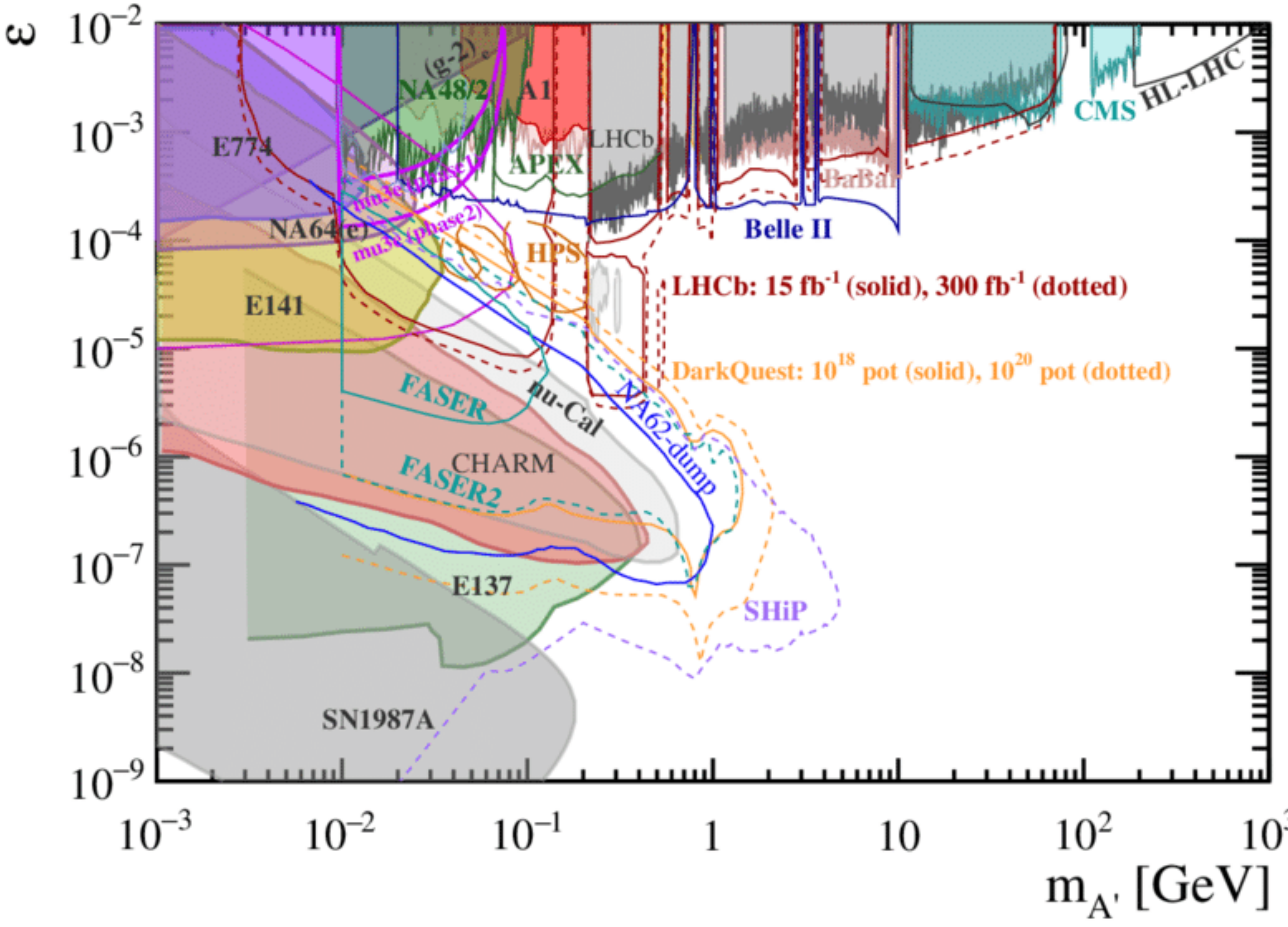


Light new particles

Sterile neutrino searches

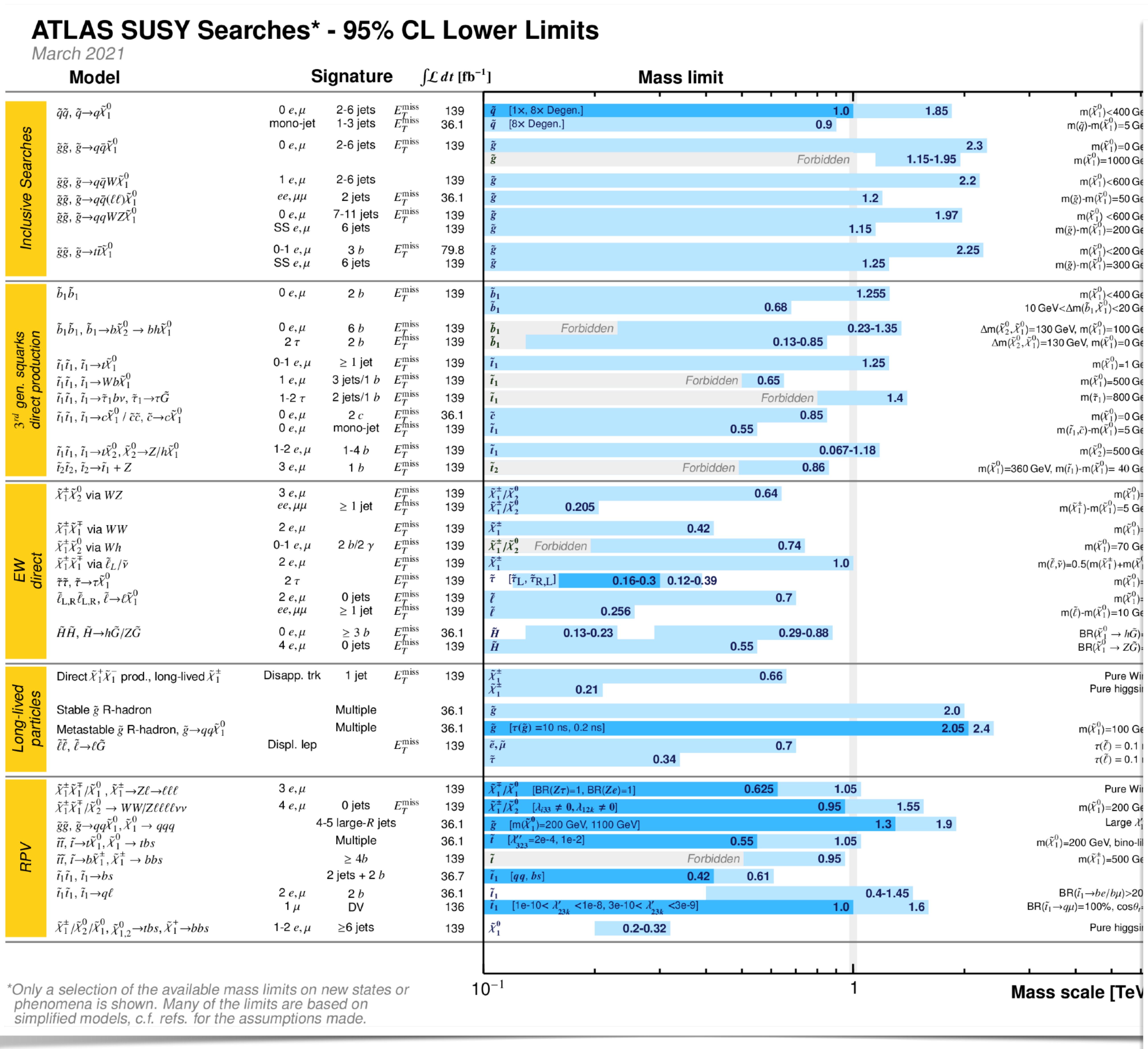


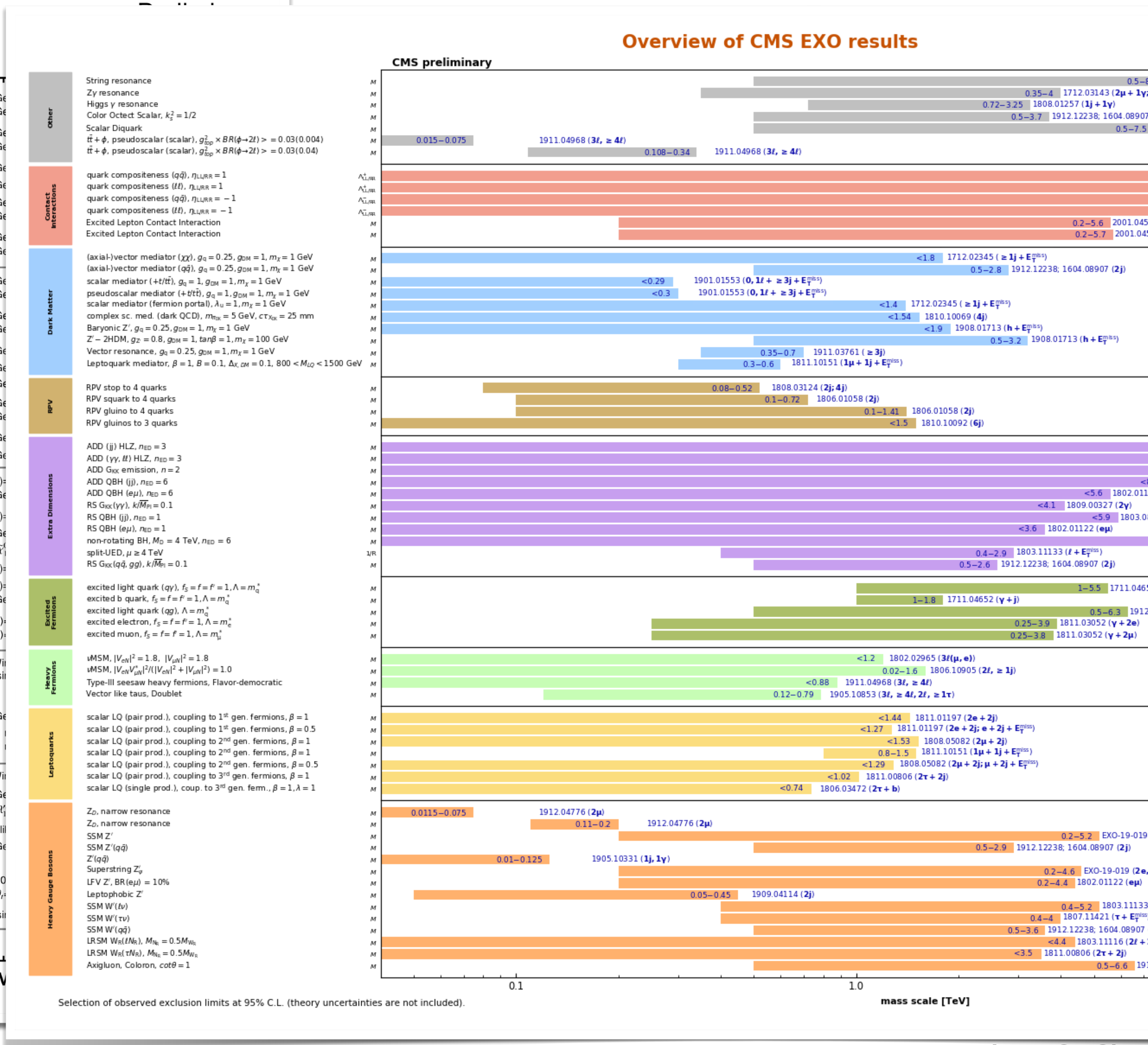
Dark photon searches



Bottom-up Effective Field Theory

New physics searches





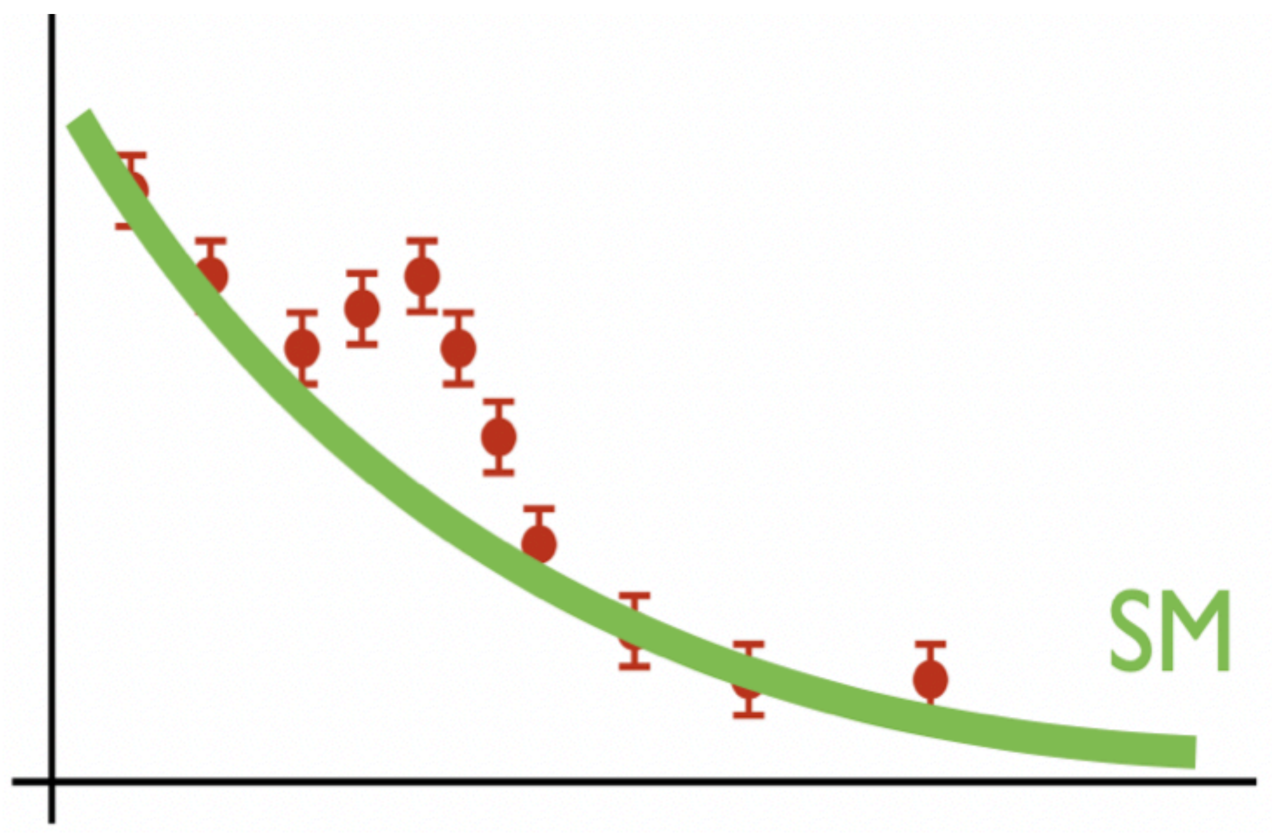
Jiang-Hao Yu (ITP-CAS)

New physics without new particle

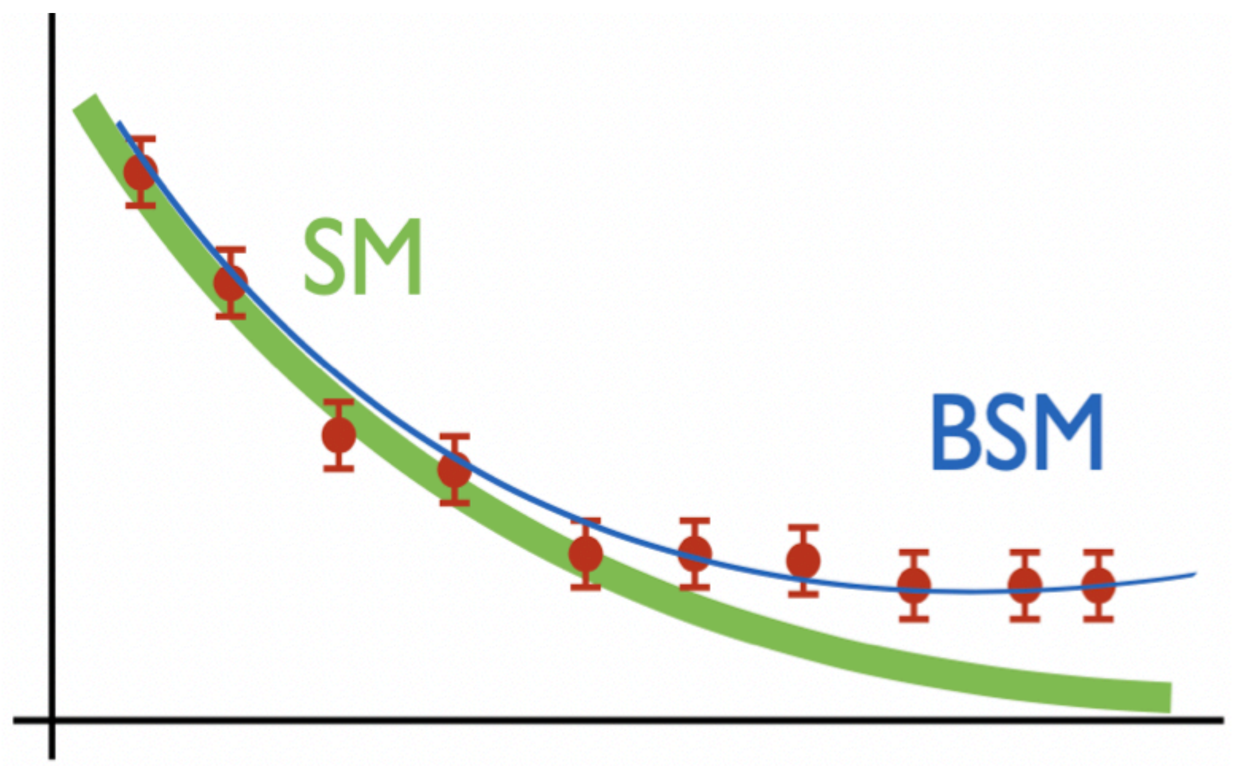
New physics beyond the LHC threshold: paradigm shift for BSM searches

Or sub-GeV light new physics

Resonance Searches



Deviation Searches



Experiments: Resonance bump hunting at the LHC

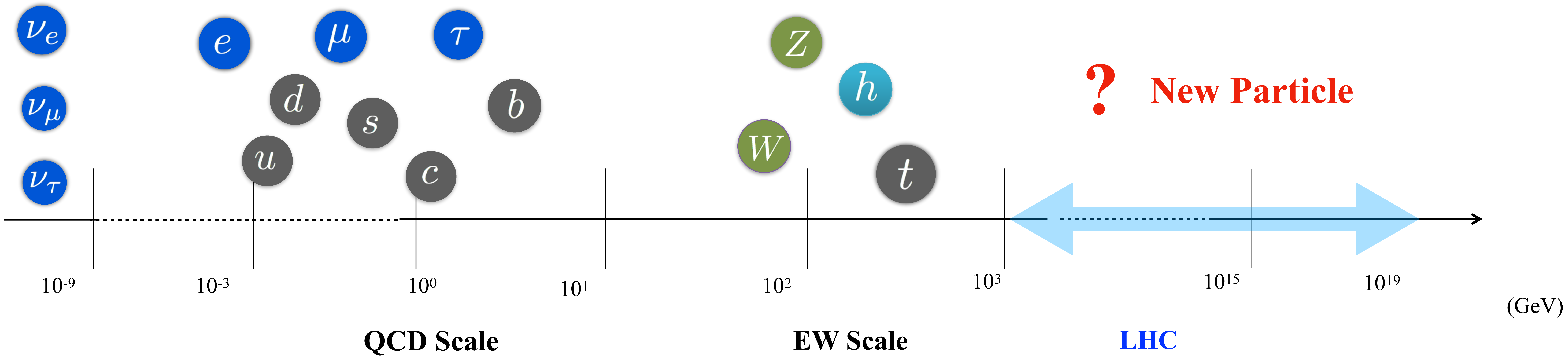
Theories: New physics model building

Experiments: deviation from SM at the LHC

Theories: Effective field theory (EFT) description

New Physics without new particles

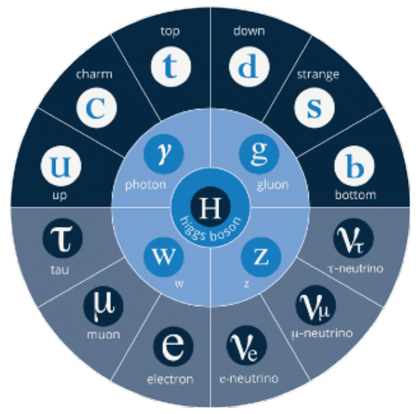
From thousand models to a unique theory



Bottom-up EFT theory

Top-down model building

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



+ new particle + new symmetry

A unique SMEFT theory

Thousands of models

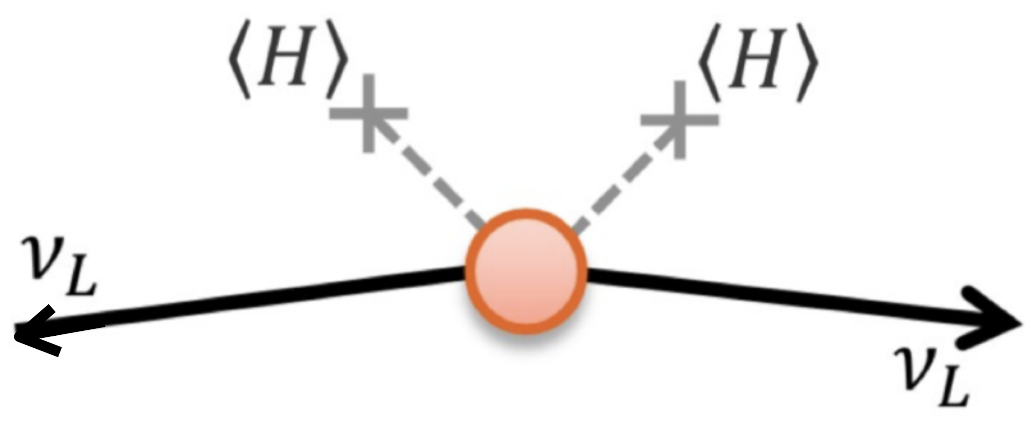
Standard model effective field theory

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

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \cdots$$

Standard Model	Weinberg Operator	Dim-6 84	30	993	560

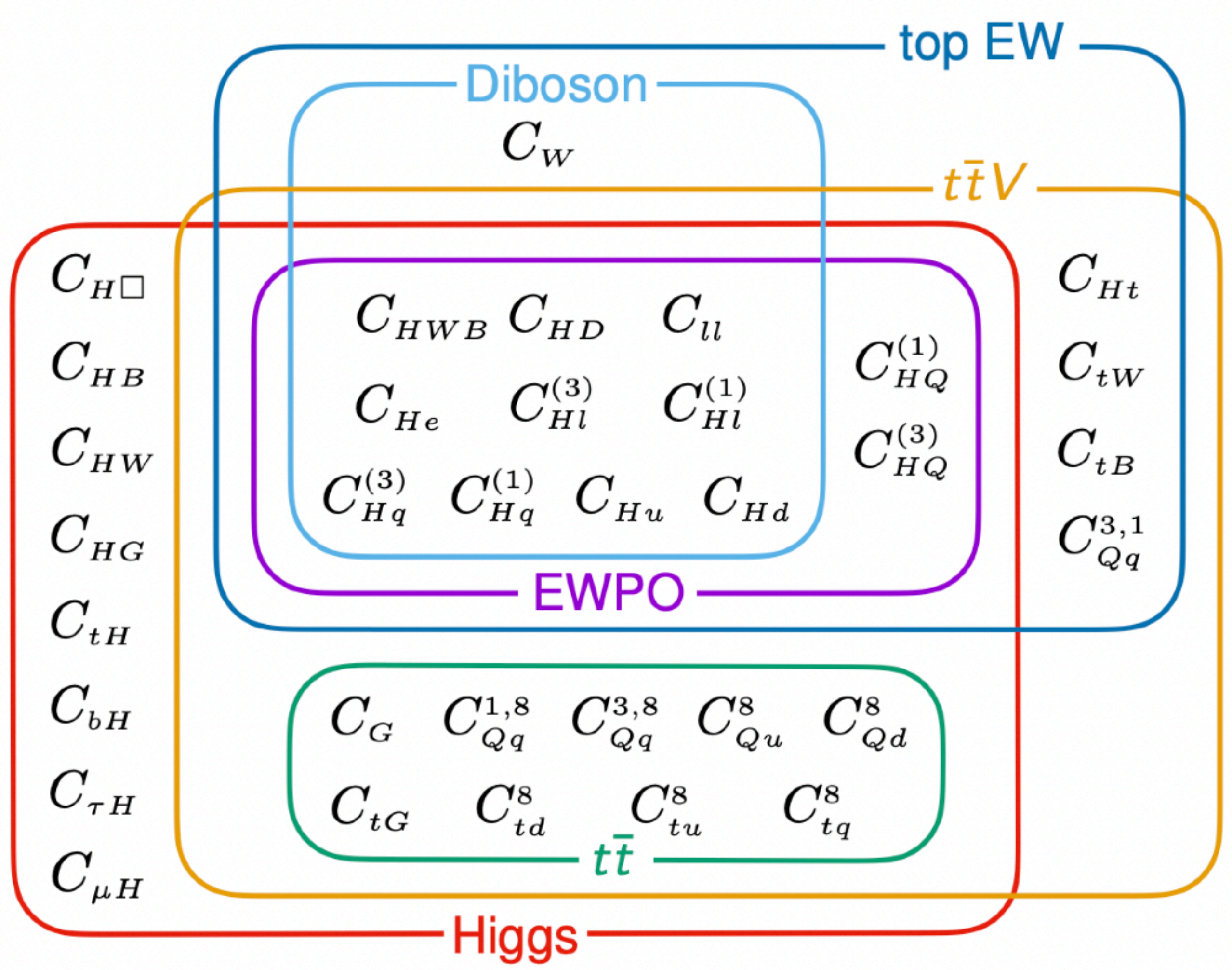
Dim-5: Weinberg operator



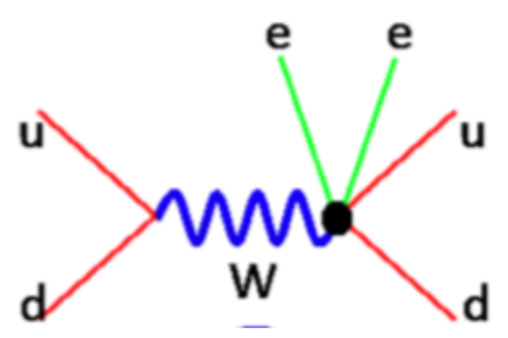
$$\frac{c_{ij}}{\Lambda}(L_iH)(L_jH) + \mathrm{h.c.}$$

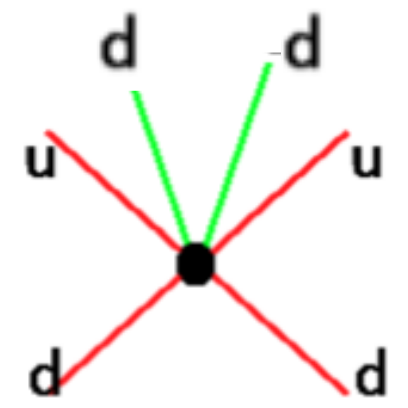
$$\to c_{ij}\frac{v^2}{\Lambda}\nu_i\nu_j + \mathrm{h.c.}$$

Dim-6: typical process

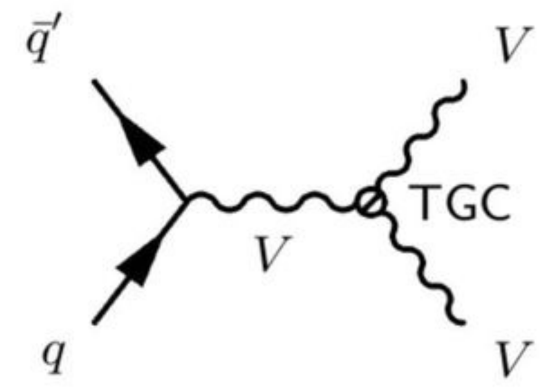


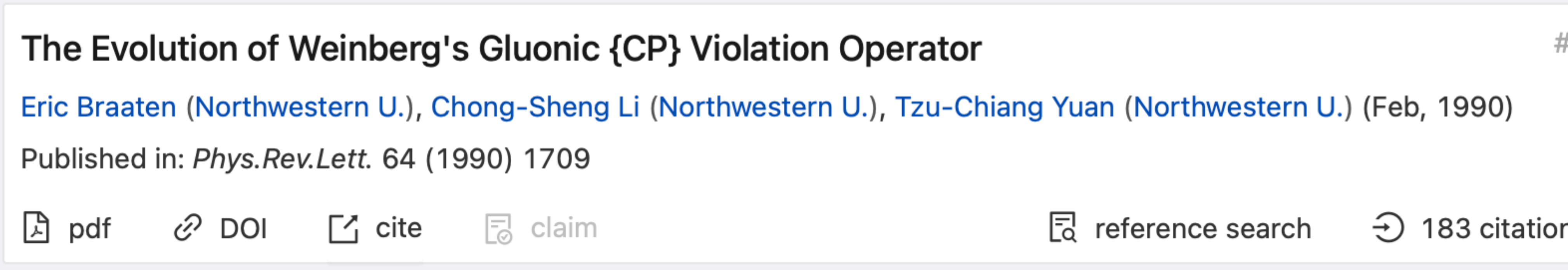
Dim-7,9: BNV, LNV





Dim-8: nTGC,




The Evolution of Weinberg's Gluonic {CP} Violation Operator

Eric Braaten (Northwestern U.), Chong-Sheng Li (Northwestern U.), Tzu-Chiang Yuan (Northwestern U.) (Feb, 1990)

Published in: *Phys.Rev.Lett.* 64 (1990) 1709

pdf DOI cite claim reference search 183 citatior

How to write general Lagrangian?

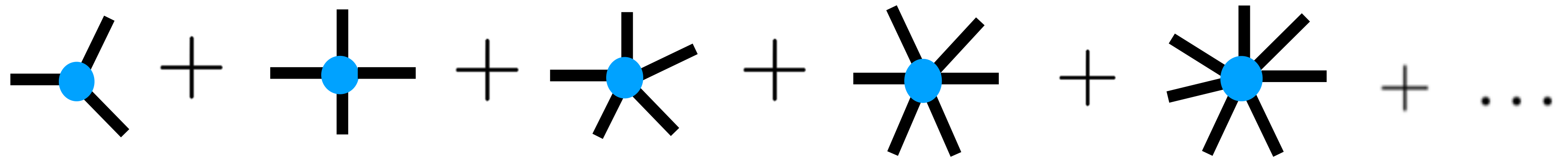
Lagrangian based on field

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

Expansion with mass dimension

Contact scattering amplitude based on particle

$\mathcal{S} =$



Classified by scattering particle numbers

[Gang Yang and Yang Zhang's talk]

$$\psi(x) = \sum_s \int \frac{d^3 p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \left[a_s(\vec{p}) u_s(\vec{p}) e^{-ip\cdot x} + b_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ip\cdot x} \right]$$

Field transform under Lorentz rep

$$A^\mu(x) \to U A^\mu(x) U^\dagger = (\Lambda^{-1})^\mu{}_\nu A^\nu(\Lambda x) + \Lambda^{-1}\partial^\nu \Omega(\Lambda x)$$

$A_\mu(x)$

Impose EOM

$\partial_\mu A^\mu = 0$

Impose gauge condition

$\epsilon^\mu(\vec{k},\lambda) \to \epsilon^\mu(\vec{k},\lambda) + \frac{k^\mu}{m}$

Particle transform under Little group

$$\varepsilon_\mu^{IJ} = \frac{\langle p^{(I}|\sigma_\mu|p^{J)}]}{\sqrt{2}m} \qquad \epsilon_\mu^+ = \frac{\langle\zeta|\sigma_\mu|\lambda]}{\sqrt{2}\langle\lambda\zeta\rangle}, \quad \epsilon_\mu^- = \frac{\langle\lambda|\sigma_\mu|\zeta]}{\sqrt{2}[\lambda\zeta]}$$

Satisfy EOM and gauge inv automatically

$$\eta_\alpha \to \eta'_\alpha = a\eta_\alpha + b\lambda_\alpha$$

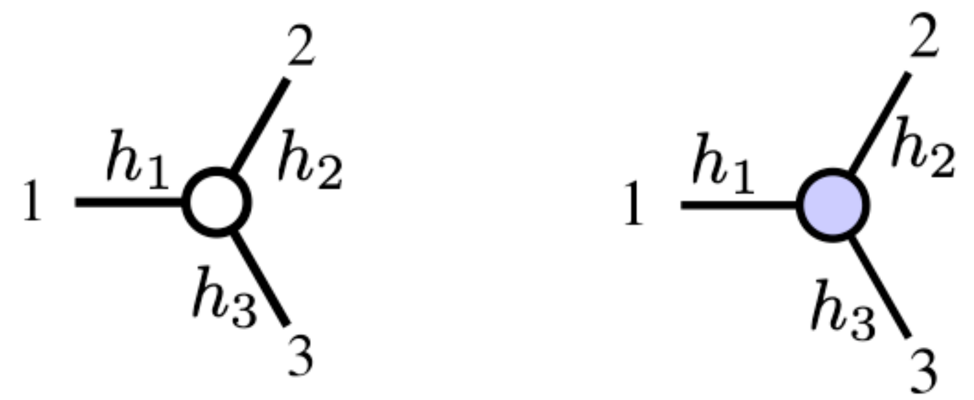
Symmetry is manifest !

Lagrangian from Poincare symmetry

The little group scaling behavior + 3-point mom. cons. determine the renormalizable interactions

$\tilde{\lambda}_1 \propto \tilde{\lambda}_2 \propto \tilde{\lambda}_3$; $\lambda_1 \propto \lambda_2 \propto \lambda_3$

$h \leq 0$ $h \geq 0$



$\langle 12\rangle^{h_3-h_1-h_2}\langle 23\rangle^{h_1-h_2-h_3}\langle 31\rangle^{h_2-h_3-h_1}$ $[12]^{h_1+h_2-h_3}[23]^{h_2+h_3-h_1}[31]^{h_3+h_1-h_2}$

[Benincasa, Cachazo, 2007]

$(--+)$ $(--+)$ $(--+)$ $(--0)$

QED Theory

Massless

$$A\left(1^{-\frac{1}{2}}2^{+\frac{1}{2}}3^{+}\right) = \frac{\langle 13\rangle^2}{\langle 12\rangle}$$

$$A\left(1^{+\frac{1}{2}}2^{-\frac{1}{2}}3^{-}\right) = \frac{[13]^2}{[12]}$$

$$\bar{\psi}\gamma^\mu\psi A_\mu$$

Yang-Mills Theory

$$A\left(1_a^- 2_b^- 3_c^+\right) = f_{abc}\frac{\langle 12\rangle^3}{\langle 13\rangle\langle 32\rangle}$$

$$A\left(1_a^+ 2_b^+ 3_c^-\right) = f_{abc}\frac{[12]^3}{[13][32]}$$

$$f_{abc}\left(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a\right)A^{\mu b}A^{\nu c}$$

Einstein Theory

$$A(1^{--}2^{--}3^{++}) = \frac{\langle 12\rangle^6}{\langle 13\rangle^2\langle 32\rangle^2}$$

$$A(1^{++}2^{++}3^{--}) = \frac{[12]^6}{[13]^2[32]^2}$$

$$\frac{h_{\mu\nu}}{\kappa}\left[\bar{g}^{\mu\nu}\bar{R} - 2\bar{R}^{\mu\nu}\right]$$

Yukawa Theory

Massless

$$A\left(1^{+\frac{1}{2}}2^{+\frac{1}{2}}3^{0}\right) = \langle 12\rangle$$

$$A\left(1^{-\frac{1}{2}}2^{-\frac{1}{2}}3^{0}\right) = [12]$$

$$\bar{\psi}\psi\phi$$

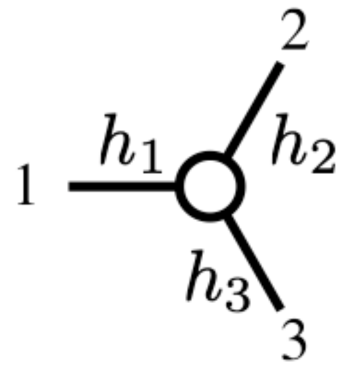
Spacetime symmetry, (not gauge symmetry), determines all 3-point local interactions

Effective operators from Poincare symmetry

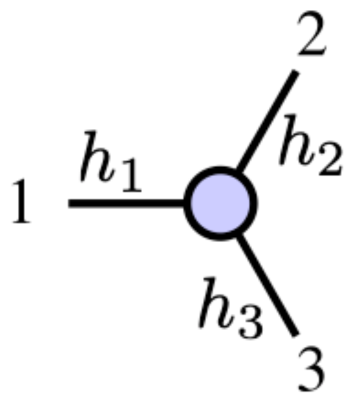
The little group scaling behavior + 3-point mom. cons. determine the non-renormalizable operators

$\tilde{\lambda}_1 \propto \tilde{\lambda}_2 \propto \tilde{\lambda}_3$;

$h \leq 0$



$\langle 12\rangle^{h_3-h_1-h_2}\langle 23\rangle^{h_1-h_2-h_3}\langle 31\rangle^{h_2-h_3-h_1}$



$\lambda_1 \propto \lambda_2 \propto \lambda_3$

$h \geq 0$

$[12]^{h_1+h_2-h_3}[23]^{h_2+h_3-h_1}[31]^{h_3+h_1-h_2}$

[Benincasa, Cachazo, 2007]

$(---)$ **Magnetic dipole QED**

Massless

$$A\left(1^{+\frac{1}{2}}2^{+\frac{1}{2}}3^{+}\right) = \langle 13\rangle\langle 23\rangle$$
$$A\left(1^{-\frac{1}{2}}2^{-\frac{1}{2}}3^{-}\right) = [13][23]$$
$$\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

$(---)$ **Dim-6 Yang-Mills**

$$A\left(1_a^- 2_b^- 3_c^-\right) = f_{abc}\langle 12\rangle\langle 23\rangle\langle 31\rangle$$
$$A\left(1_a^+ 2_b^+ 3_c^+\right) = f_{abc}[12][23][31],$$
$$f_{abc}F_\mu^{a\nu}F_\nu^{b\rho}F_\rho^{c\mu}$$

$(---)$ **Modified Gravity**

$$A(1^{--}2^{--}3^{--}) = (\langle 12\rangle\langle 23\rangle\langle 31\rangle)^2$$
$$A(1^{++}2^{++}3^{++}) = ([12][23][31])^2$$
$$R_{\mu\nu}{}^{\rho\sigma}R_{\rho\sigma}{}^{\alpha\beta}R_{\alpha\beta}{}^{\mu\nu}$$

$(-+0)$ **x**

$$A\left(1^{+\frac{1}{2}}2^{-\frac{1}{2}}3^{0}\right) = g^- \frac{\langle 13\rangle}{\langle 23\rangle} + g^+ \frac{[13]}{[23]}$$

inconsistent Locality

Spacetime symmetry, (not gauge symmetry), determines all 3-point local interactions

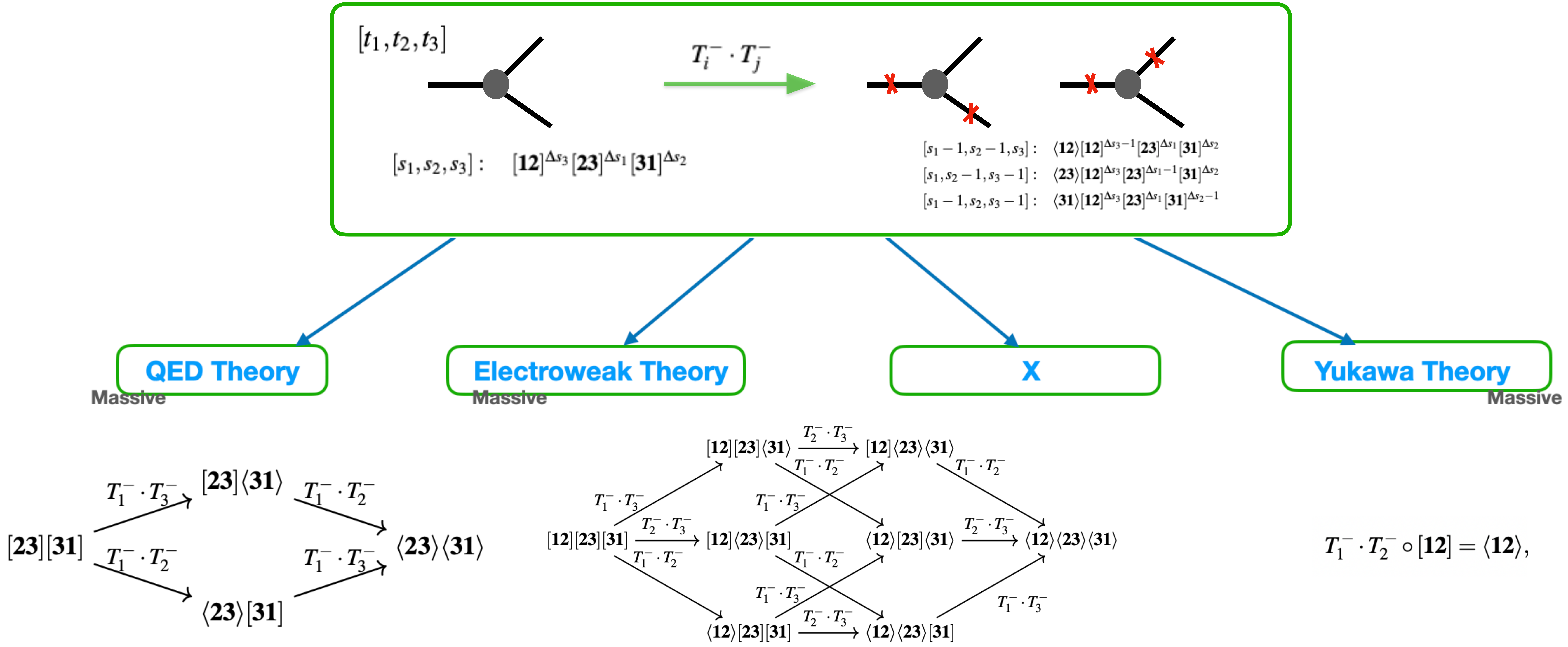
Massive operators from extended symmetry

Extend the Poincare to ISO(5,1) (4D conformal symmetry), decomposed into SO(2) x SO(3,1)

$\mathrm{CFT}:(P,K,L,D)\leftrightarrow(T^+,T^-,L,D_-)$ $\quad(\Delta,J_1,J_2)\quad$ $[t,j_1,j_2]$

Highest weight amplitudes have scaling behavior

[Yu-Han Ni, Chao Wu, Yi-Ning Wang, **J.H.Yu**, 2412.03762]



Higher point amplitude-operator correspondence

For n-point amplitudes (n>3), scaling is not enough, need larger symmetry

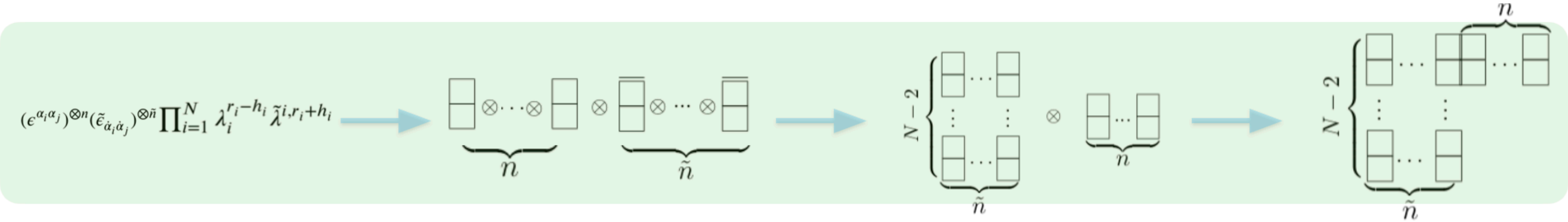
U(1)^n Little group → SL(2,C) x SU(N)

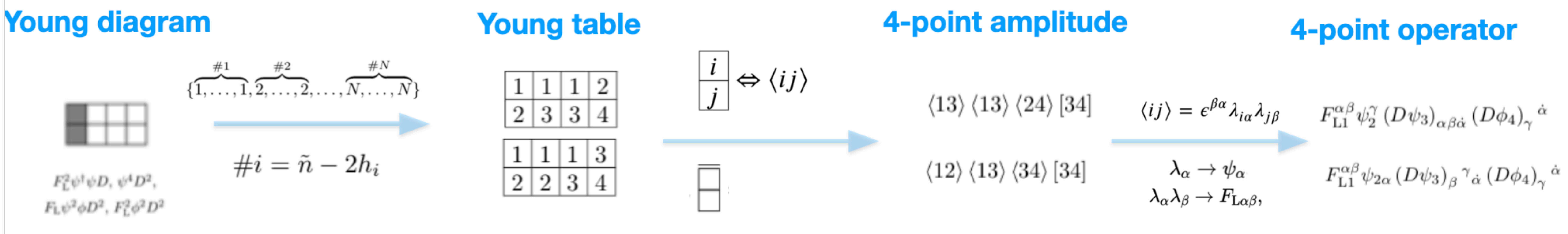
$\lambda \to t\lambda, \quad \tilde{\lambda} \to t^{-1}\tilde{\lambda}$

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

Propose Young tensor method, systematic construction of n-point amplitudes (=operator)

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





Standard model effective field theory

SMEFT provides the most general parametrization on all possible Lorentz invariant new physics

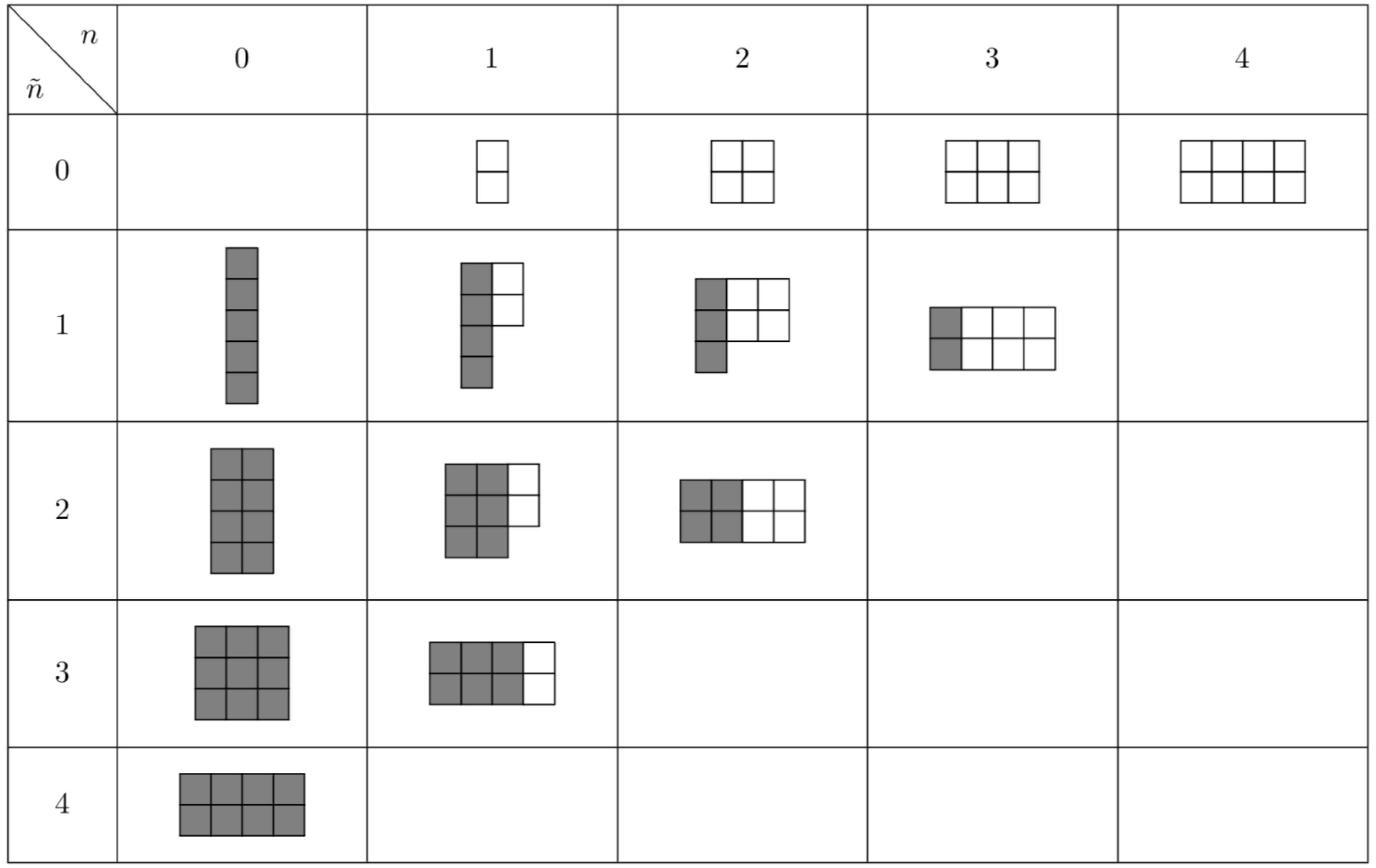
$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \cdots$$

Standard Model	Weinberg Operator	84	30	993	560

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]

$\bar{n}$ \ n	0	1	2	3	4
0	ϕ^8	$\psi^2\phi^5$	$\psi^4\phi^2$, $F_{\rm L}\psi^2\phi^3$, $F_{\rm L}^2\phi^4$	$F_{\rm L}\psi^4$, $F_{\rm L}^2\psi^2\phi$, $F_{\rm L}^3\phi^2$	$F_{\rm L}^4$
1	$\psi^{\dagger 2}\phi^5$	$\psi^{\dagger 2}\psi^2\phi^2$, $\psi^\dagger\psi\phi^4 D$, $\phi^6 D^2$	$F_{\rm L}\psi^{\dagger 2}\psi^2$, $F_{\rm L}^2\psi^{\dagger 2}\phi$, $\psi^\dagger\psi^3\phi D$, $F_{\rm L}\psi^\dagger\psi\phi^2 D$, $\psi^2\phi^3 D^2$, $F_{\rm L}\phi^4 D^2$	$F_{\rm L}^2\psi^\dagger\psi D$, $\psi^4 D^2$, $F_{\rm L}\psi^2\phi D^2$, $F_{\rm L}^2\phi^2 D^2$	
2	$\psi^{\dagger 4}\phi^2$, $F_{\rm R}\psi^{\dagger 2}\phi^3$, $F_{\rm R}^2\phi^4$	$F_{\rm R}\psi^{\dagger 2}\psi^2$, $F_{\rm R}^2\psi^2\phi$, $\psi^{\dagger 3}\psi\phi D$, $F_{\rm R}\psi^\dagger\psi\phi^2 D$, $\psi^{\dagger 2}\phi^3 D^2$, $F_{\rm R}\phi^4 D^2$	$F_{\rm R}^2 F_{\rm L}^2$, $F_{\rm R}F_{\rm L}\psi^\dagger\psi D$, $\psi^{\dagger 2}\psi^2 D^2$, $F_{\rm R}\psi^2\phi D^2$, $F_{\rm L}\psi^{\dagger 2}\phi D^2$, $F_{\rm R}F_{\rm L}\phi^2 D^2$, $\phi^4 D^4$, $\psi^\dagger\psi\phi^2 D^3$		
3	$F_{\rm R}\psi^{\dagger 4}$, $F_{\rm R}^2\psi^{\dagger 2}\phi$, $F_{\rm R}^3\phi^2$	$F_{\rm R}^2\psi^\dagger\psi D$, $\psi^{\dagger 4}D^2$, $F_{\rm R}\psi^{\dagger 2}\phi D^2$, $F_{\rm R}^2\phi^2 D^2$			
4	$F_{\rm R}^4$				



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:

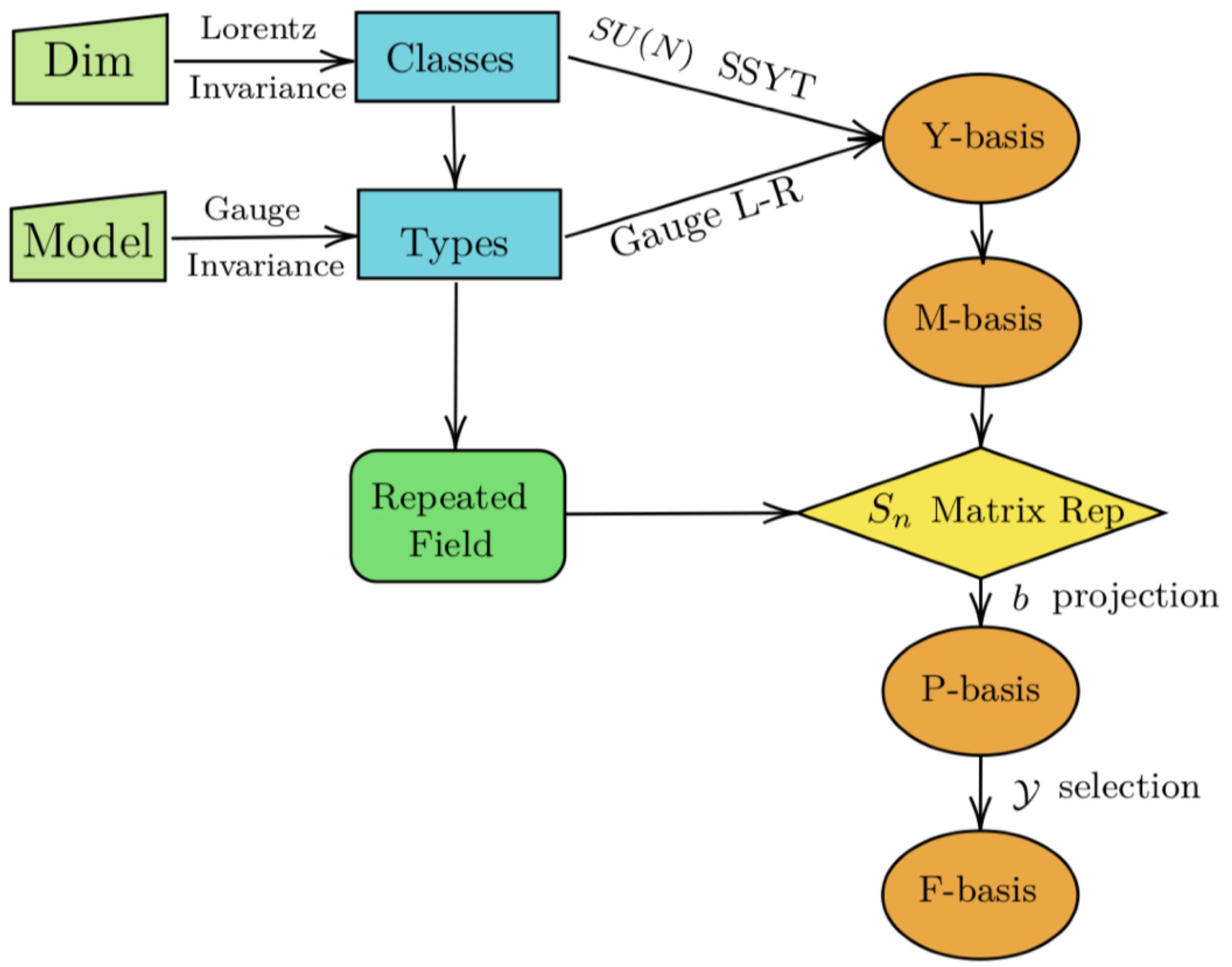
- It provides a general procedure to construct the independent and complete operator bases for generic Lorentz invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dimension.
- Various operator bases have been systematically constructed to emphasize different 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)

https://abc4eft.hepforge.org/

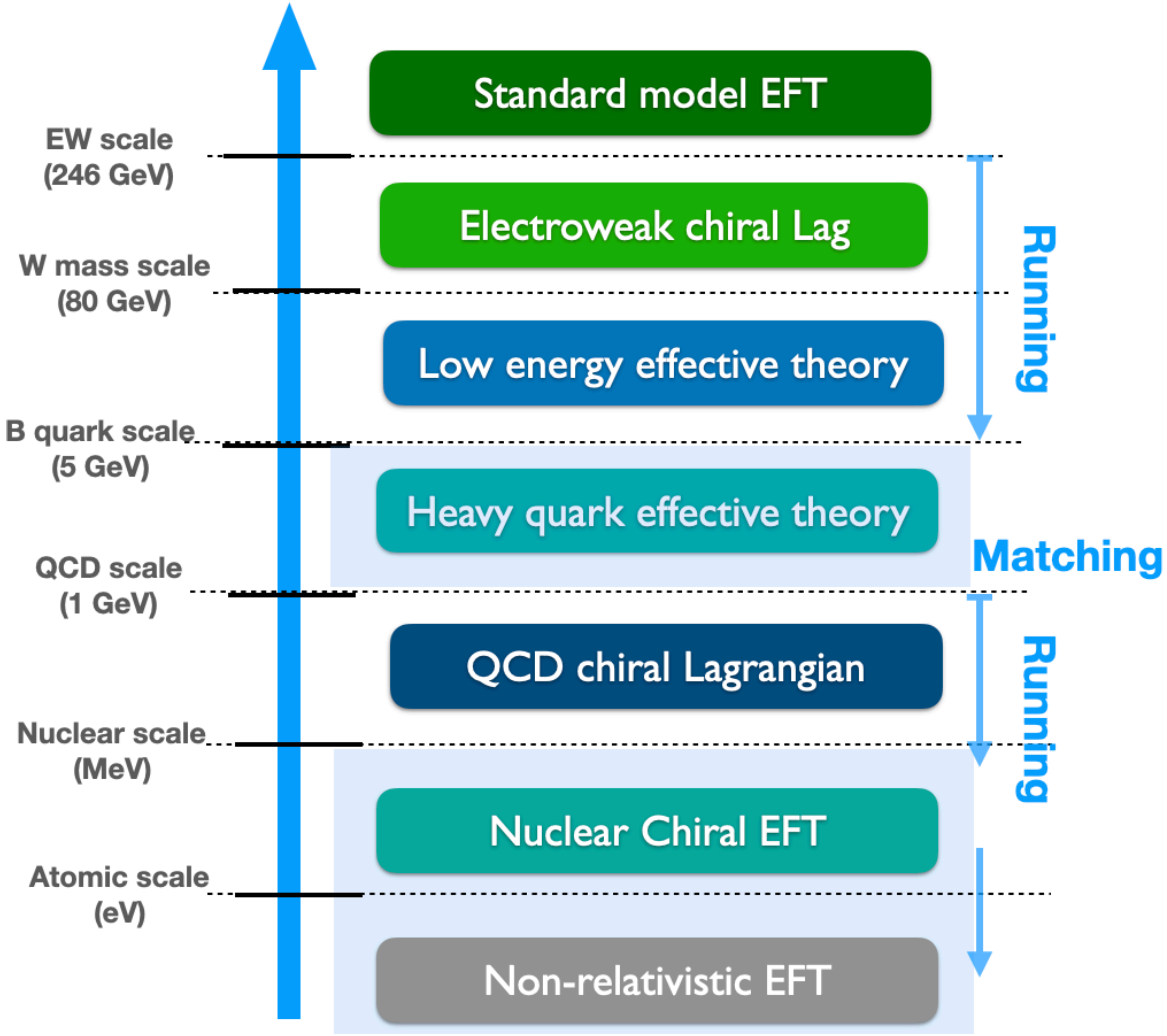


Fully Automatic

Dark matter EFT
Sterile neutrino EFT
Gravity EFT
Axion EFT
…

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, 2005.0000

[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]

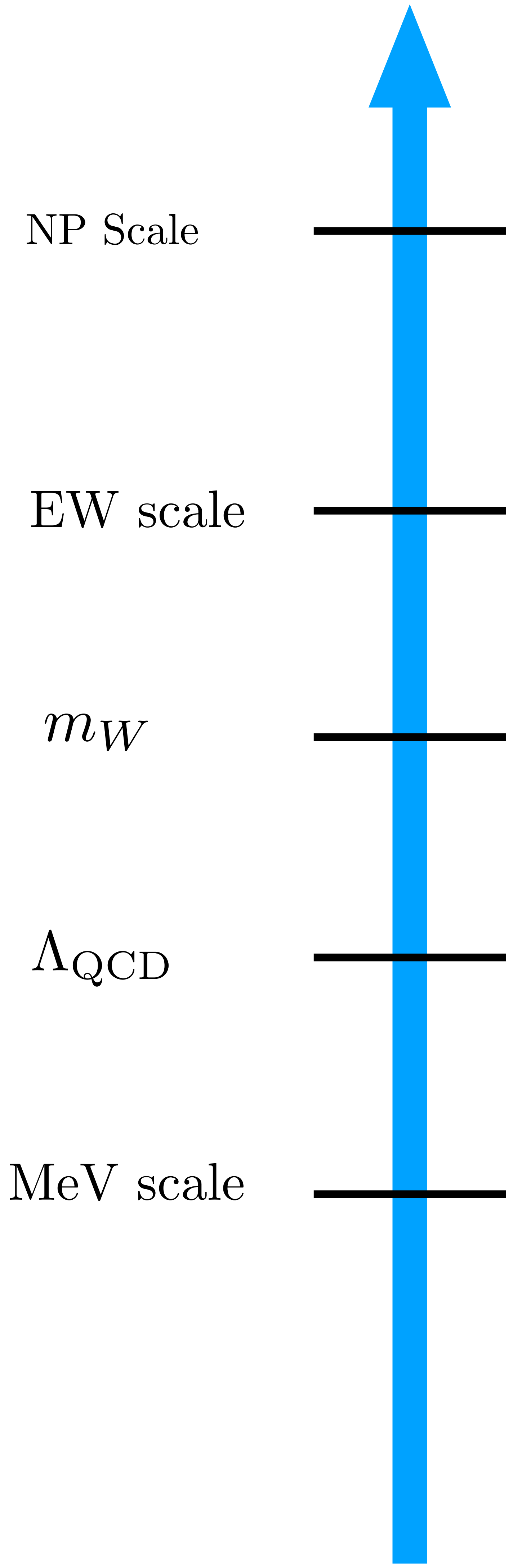
[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2501.09787]

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

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

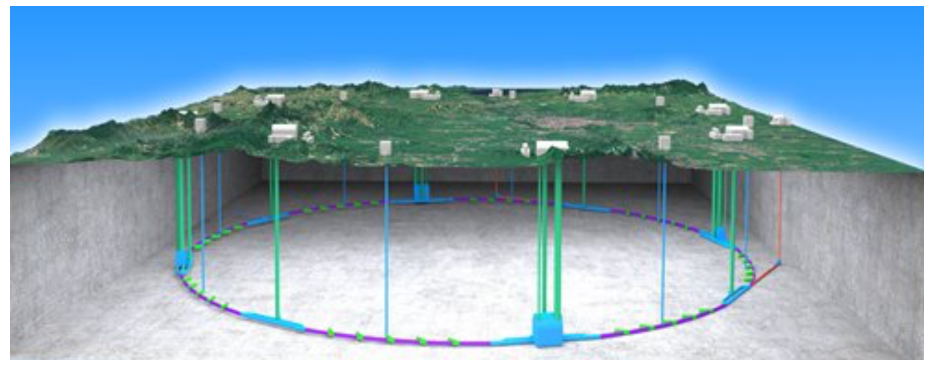
Indirect search vs direct search

EFT framework describes new physics without new particle = indirect searches

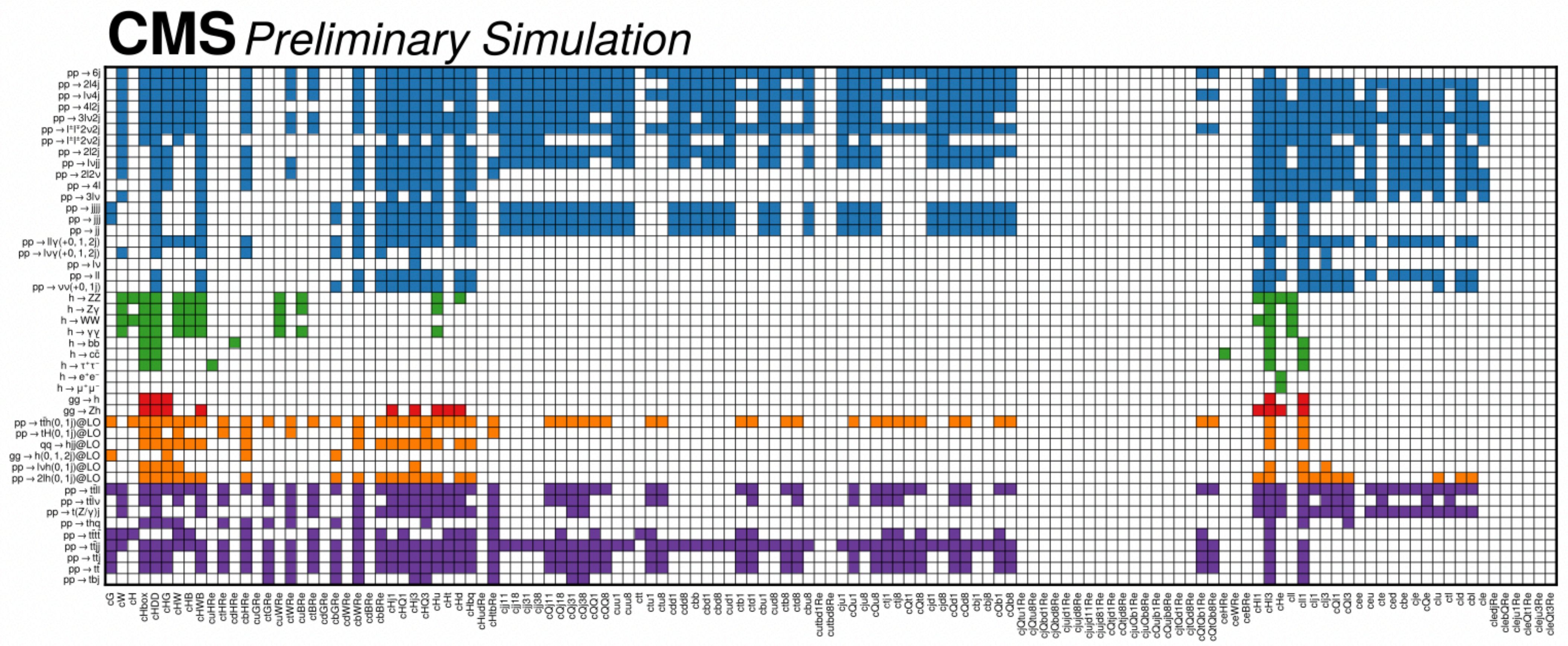


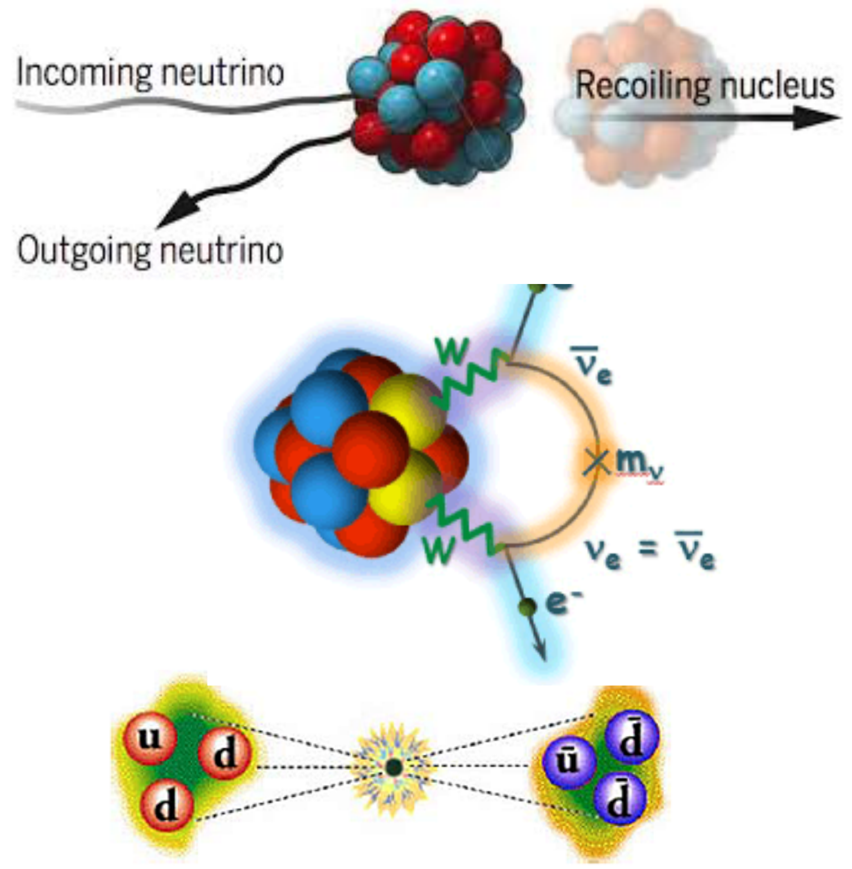
Energy frontier

high energy, high cost!



Collider probe

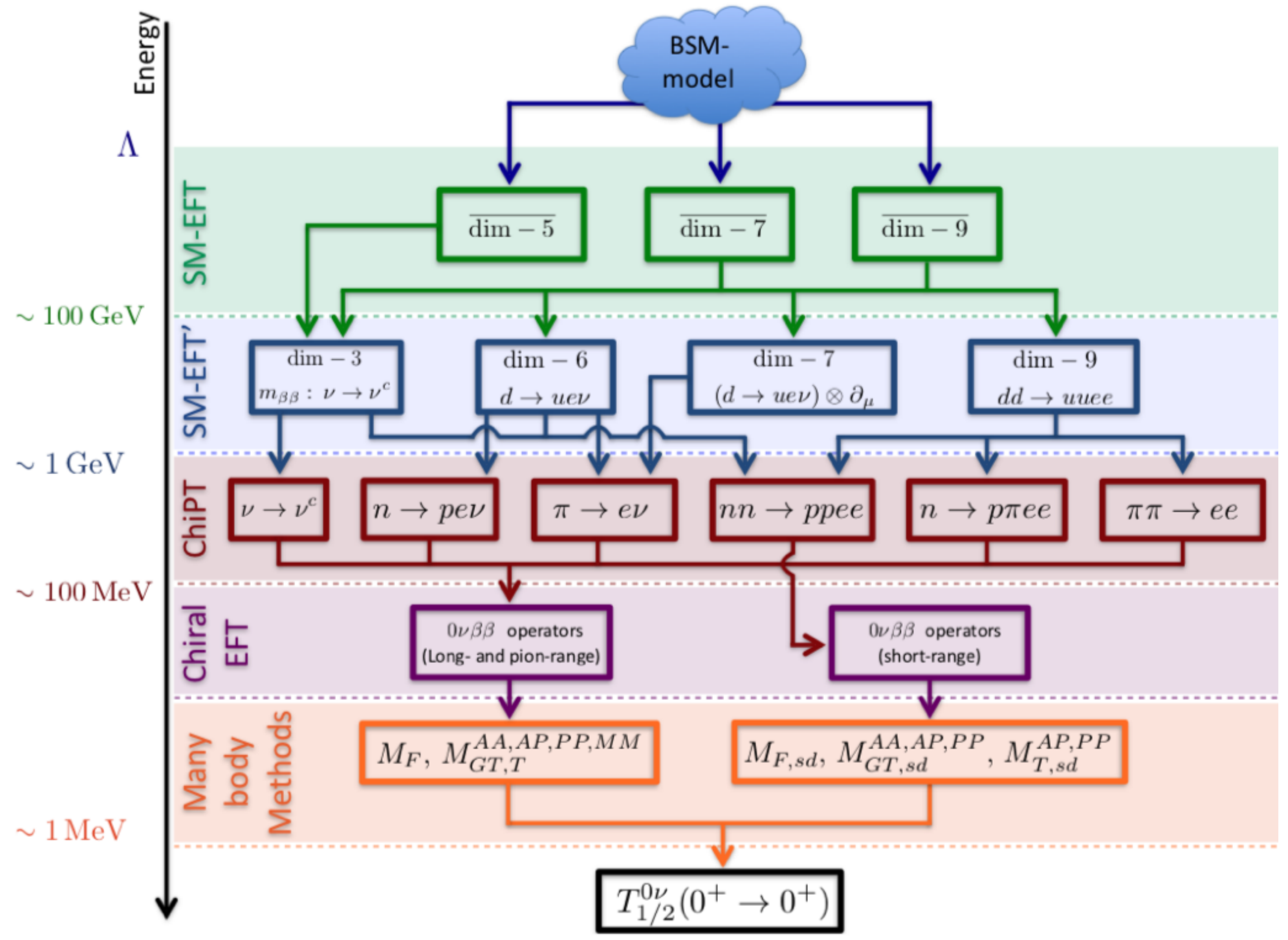




Hadronic/nuclear probe

Intensity frontier

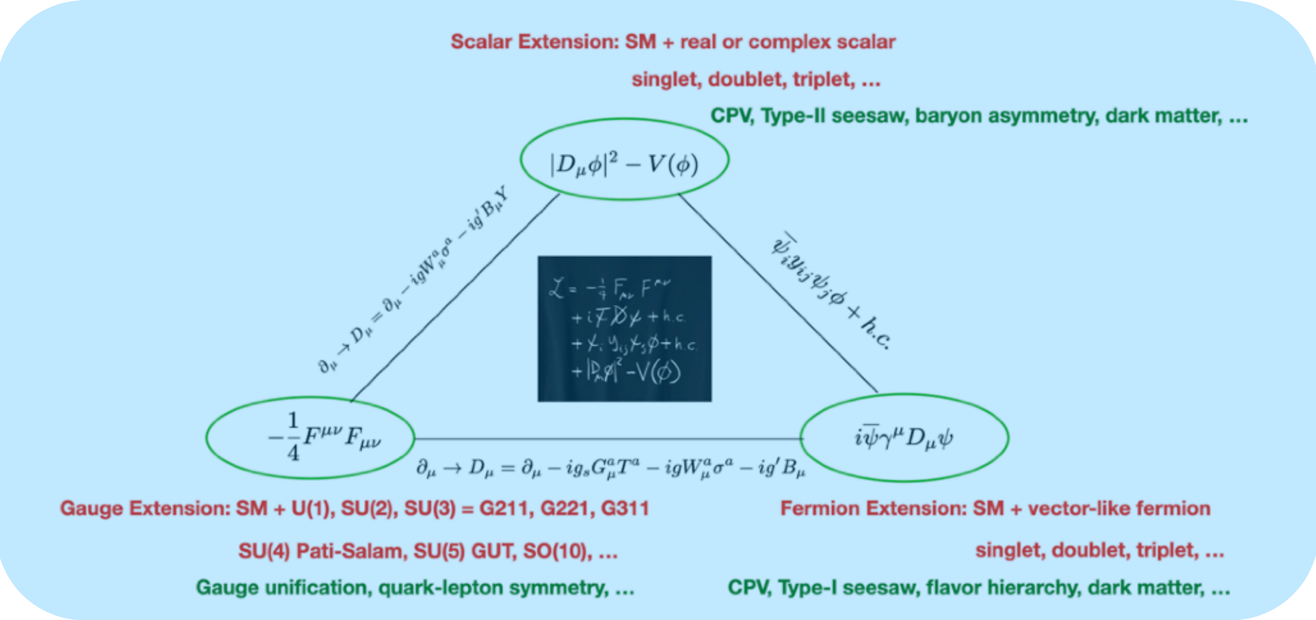
high intensity, low cost!



From indirect search to direct search

Can we get new particle systematically from EFT operators?

New physics models



New physics models are too broad and biased

New resonance from EFT operators

Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Operator	Interactions
0	1	1	0	$(H^\dagger H)(H^\dagger H)(H^\dagger H)$ $(H^\dagger H)\Box(H^\dagger H)$	$(H^\dagger H)S_1$
			1	$\epsilon_i^j\epsilon_k^l(\ell^{Ti}C\ell_j)(\bar{\ell}^k C\bar{\ell}_l^T)$	$\epsilon^{ij}(\ell_i^T C\ell_j)S_2$
			2	$(e^T Ce)(\bar{e}Ce^T)$	$(e^T Ce)S_3$
		2	1/2	$(H_j H^{\dagger j} H^{\dagger i})(H^{\dagger k} H_k H_i)$ $(\bar{q}_i d)(\bar{d} q_i)$ $(H^{\dagger j} H_j H_i)(\bar{\ell}^i e)$ $(\bar{\ell}^i e)(\bar{d} q_i)$ $(H^{\dagger j} H_j \tilde{H}_i)(\bar{q}^i u)$ $\epsilon^{ij}(\bar{\ell}_i e)(\bar{q}_j u)$ $(H^{\dagger j} H_j H_i)(\bar{q}^i d)$ $\epsilon^{ij}(\bar{q}_i u)(\bar{q}_j d)$ $\epsilon^{ij}\epsilon^{ik}(\bar{q}_j u)(\bar{u} q_k)$ $(\bar{\ell}^i e)(\bar{e}\ell_i)$	$(H^\dagger H)(H^\dagger S_4)$ $(\bar{q}^i d)S_{4i}$ $(\bar{\ell}^i e)S_{4i}$ $\epsilon^{ij}(\bar{u} q_j)S_{4i}$
		3	0	$(H^\dagger\tau^I H)(H^\dagger\tau^I H)(H^\dagger H)$ $(H_i H^{\dagger j})(H_i H^{\dagger k})(H_k H^{\dagger j})$ $(H^\dagger\tau^I H)\Box(H^\dagger\tau^I H)$ $(H^\dagger\tau^I H)(\bar{q}u\tau^I\tilde{H})$ $(H^\dagger\tau^I H)(\bar{q}d\tau^I H)$ $(H^\dagger\tau^I H)(\bar{\ell}e\tau^I H)$	$(H^\dagger\tau^I H)S_5^I$ $(H^\dagger H)(S_5^I S_5^I)$ $(\tau^I)^i_k(\tau^J)^k_j H_i H^{\dagger j} S_5^I S_5^J$

integrate-out

Bottom- and up

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \ldots$$

new physics without new particle

EFT is too conservative

Resonances from partial wave analysis

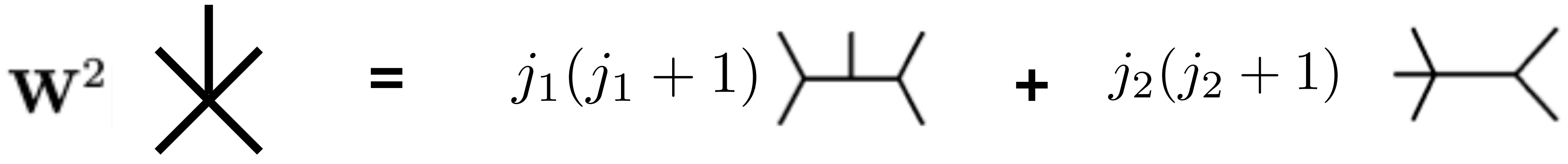
Perform partial wave on the amplitude of the effective operator [Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

J^2 in SO(3) → Pauli-Lubanski W^2 in SO(3,1)

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

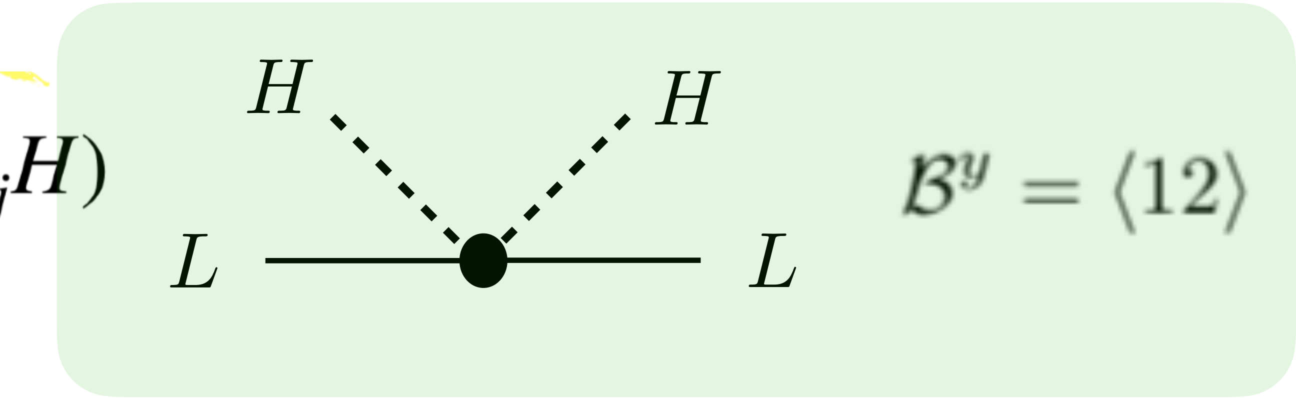
$$\mathbf{J}^2 = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\phi^2}$$

$$W^2 = \frac{1}{8}P^2(\mathrm{Tr}[M^2] + \mathrm{Tr}[\widetilde{M}^2]) - \frac{1}{4}\mathrm{Tr}[P^\intercal M P \widetilde{M}]$$



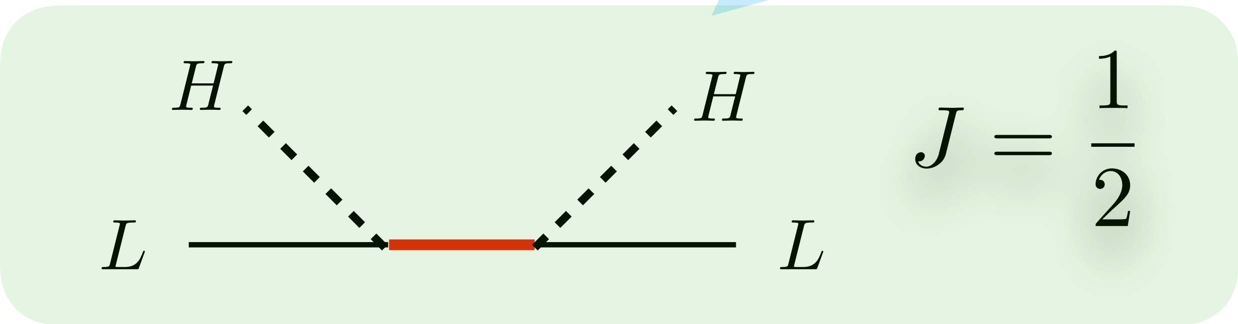
Evidence of neutrino masses is the only new physics beyond the SM

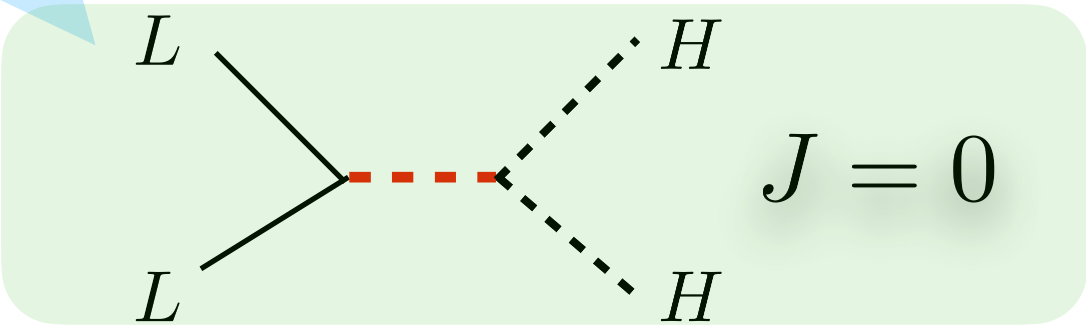
$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$



$W^2_{\{1,3\}}\mathcal{B}^y = -\frac{3}{4}s_{13}\langle 12 \rangle$ $LH \to LH$ channel

$LL \to HH$ channel $W^2_{\{1,2\}}\mathcal{B}^y = 0$





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

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

There are only 3 kinds of seesaw mechanism at tree level!

Systematic resonance searches at the LHC

Although various new physics models, there are only 47 resonances with leading effects at the LHC

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

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

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

19 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	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$

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	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$(\mathbf{6},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{6},\mathbf{2})_{\frac{5}{6}}$	$(\mathbf{8},\mathbf{1})_0$	$(\mathbf{8},\mathbf{1})_1$	$(\mathbf{8},\mathbf{3})_0$

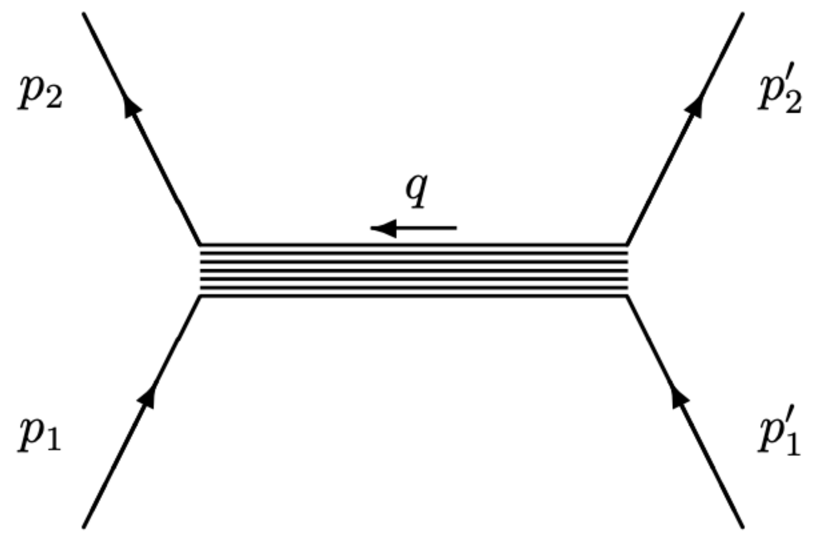
Effective way of search new physics：symmetry determines new resonances!

New way of searching new physics

New way of searching new physics

Collider searches would miss light new physics

AMO searches



$$\mathcal{O}_1 = 1\ ,$$
$$\mathcal{O}_2 = \vec{\sigma}\cdot\vec{\sigma}'\ ,$$
$$\mathcal{O}_3 = \frac{1}{m^2}\left(\vec{\sigma}\cdot\vec{q}\right)\left(\vec{\sigma}'\cdot\vec{q}\right)\ ,$$
$$\mathcal{O}_{4,5} = \frac{i}{2m^2}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\left(\vec{P}\times\vec{q}\right)\ ,$$
$$\mathcal{O}_{6,7} = \frac{i}{2m^2}\left[\left(\vec{\sigma}\cdot\vec{P}\right)\left(\vec{\sigma}'\cdot\vec{q}\right)\pm\left(\vec{\sigma}\cdot\vec{q}\right)\left(\vec{\sigma}'\cdot\vec{P}\right)\right]$$
$$\mathcal{O}_8 = \frac{1}{m^2}\left(\vec{\sigma}\cdot\vec{P}\right)\left(\vec{\sigma}'\cdot\vec{P}\right)\ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\vec{q}\ ,$$
$$\mathcal{O}_{11} = \frac{i}{m}\left(\vec{\sigma}\times\vec{\sigma}'\right)\cdot\vec{q}\ ,$$
$$\mathcal{O}_{12,13} = \frac{1}{2m}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\vec{P}\ ,$$
$$\mathcal{O}_{14} = \frac{1}{m}\left(\vec{\sigma}\times\vec{\sigma}'\right)\cdot\vec{P}\ ,$$
$$\mathcal{O}_{15} = \frac{1}{2m^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{P}\times\vec{q}\right)\right]\left(\vec{\sigma}'\cdot\vec{q}\right)+\left(\vec{\sigma}\cdot\vec{q}\right)\left[\vec{\sigma}'\cdot\left(\vec{P}\times\vec{q}\right)\right]\right\}$$
$$\mathcal{O}_{16} = \frac{i}{2m^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{P}\times\vec{q}\right)\right]\left(\vec{\sigma}'\cdot\vec{P}\right)+\left(\vec{\sigma}\cdot\vec{P}\right)\left[\vec{\sigma}'\cdot\left(\vec{P}\times\vec{q}\right)\right]\right\}$$

Jiang-Hao Yu (ITP-CAS)

NR theory from Poincare SSB

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

In non-relativistic field theory, the anti-particle dof is hidden, described by spacetime symmetry breaking

Poincare Group

$$\begin{cases} \hat{P}^\mu, & \text{Translations}, \\ \hat{J}^i, & \text{Rotations}, \\ \hat{K}^i, & \text{Boosts}, \end{cases}$$

$$R^4 \rtimes SO(3,1)$$

$$\langle\Omega|\hat{P}^\mu|\Omega\rangle \equiv m v^\mu$$

$$v_0^\mu = (1,0,0,0)$$

Spin Group

$$\begin{cases} \hat{H}_v = v \cdot \hat{P} & , \quad \text{Time Translation}, \\ (\hat{P}_v)^i = v_\perp^i \cdot \hat{P} & , \quad \text{Spatial Translations}, \\ (\hat{J}_v)^i = (v_\perp^i)^\mu \epsilon_{\mu\nu\rho\sigma} \hat{J}^{\nu\rho} v^\sigma & , \quad \text{Rotations}, \end{cases}$$

$$R^{1,3} \rtimes SO(3)$$

CCWZ Coset

$$v^\mu = L(\vec{\eta}(v))v_0^\mu \quad L(\vec{\eta}) = e^{i\vec{\eta}\cdot\vec{K}}$$

Missing Goldstone

$$|v,0,\sigma\rangle + |v,\vec{k}\rangle = |v,\vec{k},\sigma\rangle$$

Rest state **Goldstone** **k state**

$$|v,\vec{k},\sigma\rangle = U(L_v(k))|v,0,\sigma\rangle$$

Boost relates different k

Shift symmetry

$$\text{rotation}: \vec{\eta} \to \quad \vec{\eta}\,' = R\vec{\eta},$$

$$\text{boost}: \vec{\eta} \to \quad \vec{\eta}\,' = \vec{\eta} + \frac{\vec{q}}{m} + \mathcal{O}(q^2).$$

$$v^\mu \to v^\mu + \frac{q^\mu}{m}$$

Reparametrization Invariance

Amplitudes from nonlinear symmetry

Heavy particle effective theory (NR particle + photon, gluon, graviton, axion, etc)

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

3-pt scaling for highest weight

$$|k^+\rfloor \equiv (\psi^+)^s_I \qquad |k^-\rfloor \equiv (\psi^-)^s_I$$

$$\lceil 1^\pm 2^\pm \rfloor^{S_1+S_2-S_3} \lceil 1^\pm 3^\pm \rfloor^{S_1+S_3-S_2} \lceil 2^\pm 3^\pm \rfloor^{S_2+S_3-S_1}$$

$$|k^-\rfloor = \frac{1}{2m + v\cdot k}|k^+\rfloor .$$

Direct construction

dim	Operators
5	$N^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B} N$ $\quad N^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B}\chi$ $\quad \chi^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B}\chi$
6	$N^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B}\partial_t N$ $\quad N^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B}\partial_t\chi$ $\quad \chi^\dagger \boldsymbol{\sigma}\cdot \boldsymbol{B}\partial_t\chi$ $N^\dagger \boldsymbol{\sigma}\cdot \partial_t\boldsymbol{B} N$ $\quad N^\dagger \boldsymbol{\sigma}\cdot \partial_t\boldsymbol{B}\chi$ $\quad \chi^\dagger \boldsymbol{\sigma}\cdot \partial_t\boldsymbol{B}\chi$

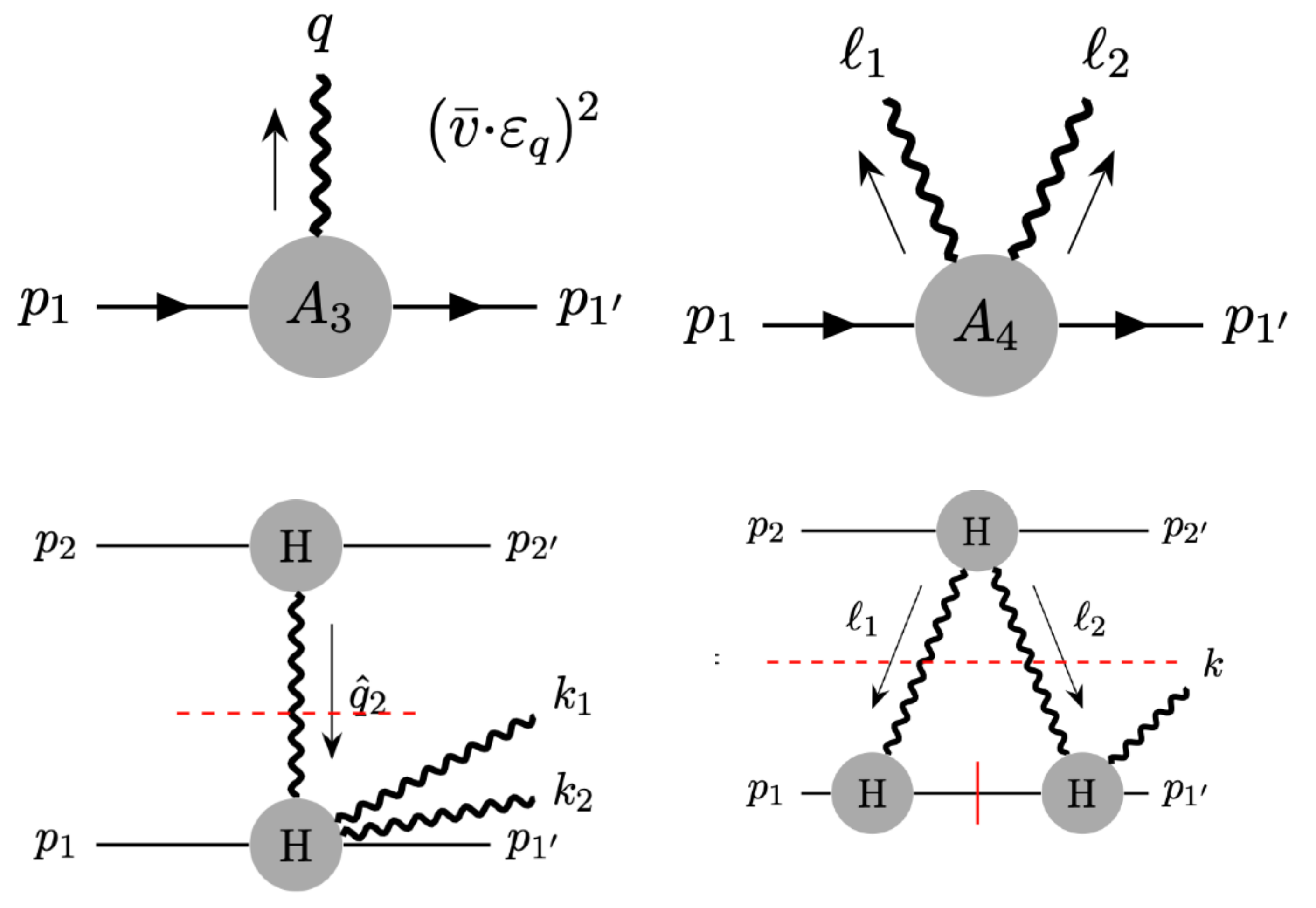
Amplitudes		
$\lceil 12^+\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^-\rfloor$
$(v\cdot k_2)\times$ $\lceil 12^+\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^-\rfloor$
$(v\cdot q_1)\times$ $\lceil 12^+\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^+\rfloor$	$\lceil 12^-\rfloor\lceil 13^-\rfloor$

Linear RPI

Heavy quark effective theory

dim	Amplitudes	Operators
5	$\lceil 12^+\rfloor\lceil 13^+\rfloor$	$N^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{B}N$
6	$\lceil 12^+\rfloor\lceil 1\vert q_{1\perp}\vert 3^+\rfloor$	$N^\dagger\epsilon^{ijk}\sigma^i[\nabla^j, B^k]N$
	$\lceil 12^+\rfloor\lceil 1\vert k_{2\perp}\vert 3^+\rfloor$	$N^\dagger\boldsymbol{B}\cdot\boldsymbol{D}N$
	$\lceil 13^+\rfloor\lceil 1\vert k_{2\perp}\vert 2^+\rfloor$	$N^\dagger\epsilon^{ijk}\sigma^i B^j D^k N$
7	$\lceil 1\vert q_{1\perp}\vert 2^+\rfloor\lceil 1\vert k_{2\perp}\vert 3^+\rfloor$	$N^\dagger\epsilon^{ijk}\{D^i,[\partial^j B^k]\}N$
	$\lceil 1\vert q_{1\perp}\vert 2^+\rfloor\lceil 1\vert q_{1\perp}\vert 3^+\rfloor$	$N^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{D}\boldsymbol{B}\cdot\boldsymbol{D}N$
	$\lceil 1\vert k_{2\perp}\vert 2^+\rfloor\lceil 1\vert k_{2\perp}\vert 3^+\rfloor$	$N^\dagger\boldsymbol{D}\cdot\boldsymbol{B}\boldsymbol{\sigma}\cdot\boldsymbol{D}N$
	$\mathrm{tr}[q_{1\perp}q_{1\perp}]\lceil 12^+\rfloor\lceil 13^+\rfloor$	$N^\dagger[\partial^2,\boldsymbol{\sigma}\cdot\boldsymbol{B}]N$
	$\mathrm{tr}[k_{2\perp}k_{2\perp}]\lceil 12^+\rfloor\lceil 13^+\rfloor$	$N^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{B}D^2N$
	$\mathrm{tr}[q_{1\perp}k_{2\perp}]\lceil 12^+\rfloor\lceil 13^+\rfloor$	$N^\dagger\epsilon_{ijk}D^i\boldsymbol{\sigma}\cdot\boldsymbol{B}D^iN$

Heavy black hole effective theory

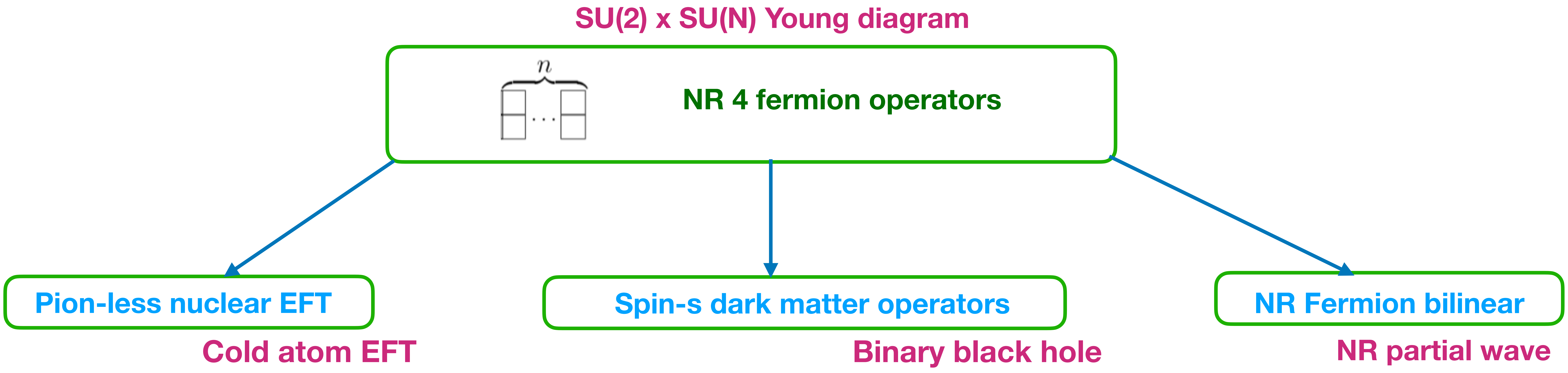


Jiang-Hao Yu (ITP-CAS)

Nonrelativistic effective theory

NR 4-fermion operators, can be described by SU(2) Young diagram

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



Integrate-out amplitudes		Operators
$\lceil 1^+2^+\rfloor\lceil 3^+4^+\rfloor$	$\lceil 1^+3^+\rfloor\lceil 2^+4^+\rfloor$	$(N^\dagger N)(N^\dagger N)\quad(N^\dagger\boldsymbol{\sigma}N)\cdot(N^\dagger\boldsymbol{\sigma}N)$
$\lceil 1^+\vert k_{2\perp}\vert 2^+\rfloor\lceil 3^+\vert k_{2\perp}\vert 4^+\rfloor$	$\lceil 1^+\vert k_{2\perp}\vert 3^+\rfloor\lceil 2^+\vert k_{2\perp}\vert 4^+\rfloor$	$: (N^\dagger\vec{\sigma}\cdot\overrightarrow{\nabla}\overrightarrow{\nabla}^i N^\dagger)(N\sigma^i N)+h.c.$
$\lceil 1^+\vert k_{2\perp}k_{2\perp}\vert 2^+\rfloor\lceil 3^+4^+\rfloor$	$\lceil 1^+3^+\rfloor\lceil 2^+\vert k_{3\perp}k_{2\perp}\vert 4^+\rfloor$	$: -(N^\dagger\overrightarrow{\nabla}^2 N^\dagger)(NN)+h.c.$
$\lceil 1^+\vert k_{2\perp}k_{3\perp}\vert 2^+\rfloor\lceil 3^+4^+\rfloor$	$\lceil 1^+\vert k_{2\perp}k_{3\perp}\vert 4^+\rfloor\lceil 2^+3^+\rfloor$	$: -(N^\dagger\vec{\sigma}\cdot\overrightarrow{\nabla}\sigma^i N^\dagger)(N\overleftarrow{\nabla}^i N)+h.c.$
$\lceil 1^+\vert k_{2\perp}\vert 2^+\rfloor\lceil 3^+\vert k_{3\perp}\vert 4^+\rfloor$	$\lceil 1^+2^+\rfloor\lceil 3^+4^+\rfloor tr[k_{2\perp}k_{3\perp}]$	$: -(N^\dagger\vec{\sigma}\cdot\overrightarrow{\nabla}N^\dagger)(N\vec{\sigma}\cdot\overleftarrow{\nabla}N)+h.c.$
$\lceil 1^+3^+\rfloor\lceil 2^+4^+\rfloor tr[k_{2\perp}k_{4\perp}]$	$\lceil 1^+\vert k_{2\perp}k_{4\perp}\vert 3^+\rfloor\lceil 2^+4^+\rfloor$	$: -2(N^\dagger N)(N^\dagger\overleftarrow{\nabla}\cdot\overrightarrow{\nabla}N)+h.c.$
$\lceil 1^+\vert k_{2\perp}k_{4\perp}\vert 4^+\rfloor\lceil 2^+3^+\rfloor$	$\lceil 1^+\vert k_{2\perp}\vert 2^+\rfloor\lceil 3^+\vert k_{4\perp}\vert 4^+\rfloor$	$: (N^\dagger\sigma^i\sigma^j N)(N^\dagger\overleftarrow{\nabla}^i\overrightarrow{\nabla}^j N)+h.c.$

Young tableau	Amplitudes	Operators
$i_1\ i_3$ / $i_2\ i_4$	$\lceil 1^+2^+\rfloor\lceil 3^+4^+\rfloor$	$(N_1^\dagger N_2)(\xi_3^\dagger\xi_4)$
$i_1\ i_2$ / $i_3\ i_4$	$\lceil 1^+3^+\rfloor\lceil 2^+4^+\rfloor$	$(N_1^\dagger\xi_3^\dagger)(N_2\xi_4)$
$i_1\ i_2\ j_2$ / $j_2\ i_3\ i_4$	$-\lceil 1^+\vert k_{2\perp}\vert 4^+\rfloor\lceil 2^+3^+\rfloor$	$-(N_1^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}_2\xi_4)(N_2\xi_3^\dagger)$
$i_1\ i_2\ i_3$ / $j_2\ j_2\ i_4$	$\lceil 1^+\vert k_{2\perp}\vert 2^+\rfloor\lceil 3^+4^+\rfloor$	$(N_1^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}_2N_2)(\xi_3^\dagger\xi_4)$
$i_1\ j_2\ j_2$ / $i_2\ i_3\ i_4$	$\lceil 1^+2^+\rfloor\lceil 3^+\vert k_{2\perp}\vert 4^+\rfloor$	$(N_1^\dagger N_2)(\xi_3^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}_2\xi_4)$
$i_1\ i_2\ i_3$ / $j_3\ j_3\ i_4$	$\lceil 1^+\vert k_{3\perp}\vert 2^+\rfloor\lceil 3^+4^+\rfloor$	$(N_1^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}_3N_2)(\xi_3^\dagger\xi_4)$

	Amp	$^{2S+1}L_J$	C	P
NN	$\lfloor 1^+2^+\rfloor$	$^1S_0$	\	+
$N\sigma^i N$	$\vert 1^+\rfloor^{(I}\vert 2^+\rfloor^{J)}$	$^3S_1$	\	+
$N\overleftrightarrow{\nabla}^i N$	$q^{IJ}\lfloor 1^+2^+\rfloor$	$^1P_0$	\	-
$N(\overleftrightarrow{\nabla}\cdot\sigma)N$	$\lfloor 1^+\vert\mathrm{q}\vert 2^+\rfloor$	$^3P_0$	\	-
$N\overleftrightarrow{\nabla}\times\vec{\sigma}N$	$q_I^K\vert 1^+\rfloor^{(I}\vert 2^+\rfloor^{J)}$	$^3P_1$	\	-
$N(\overleftrightarrow{\nabla}^i\vec{\sigma}^j-\frac{\overleftrightarrow{\nabla}\cdot\sigma}{3}\delta^{ij})N$	$q^{(KL}\vert 1^+\rfloor^I\vert 2^+\rfloor^{J)}$	$^3P_2$	\	-

Goldstone EFT from spacetime breaking

Spontaneous symmetry breaking: boost, translation, rotation

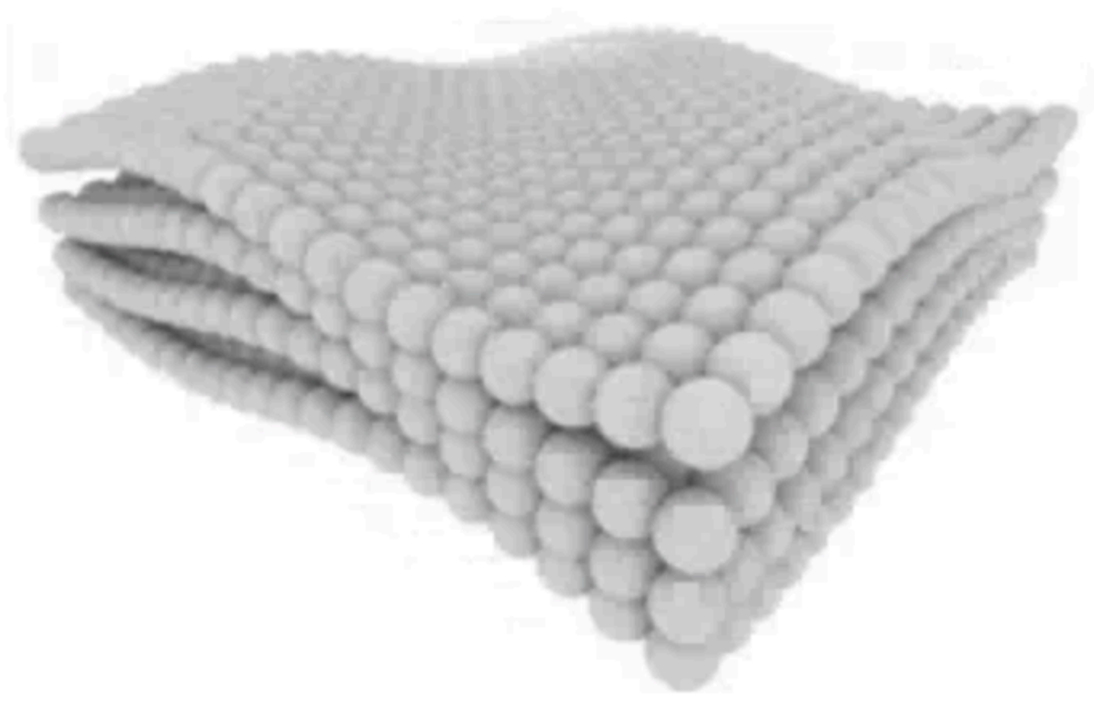
[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in progress]

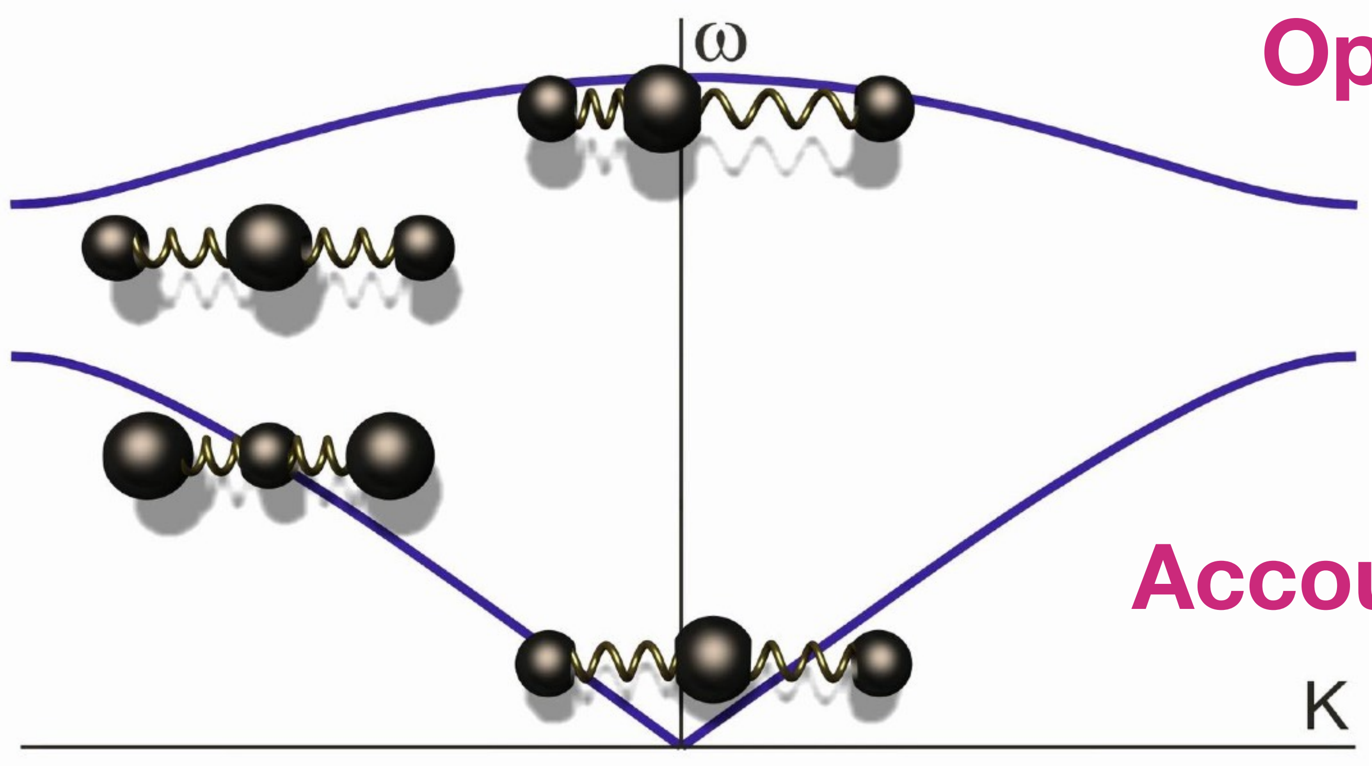
Spontaneous breaking of spatial translation: Phonon as Goldstone boson

Superfluid

$$\Phi \to e^{ia}\Phi$$

$$\langle \Phi(x) \rangle = e^{it}$$



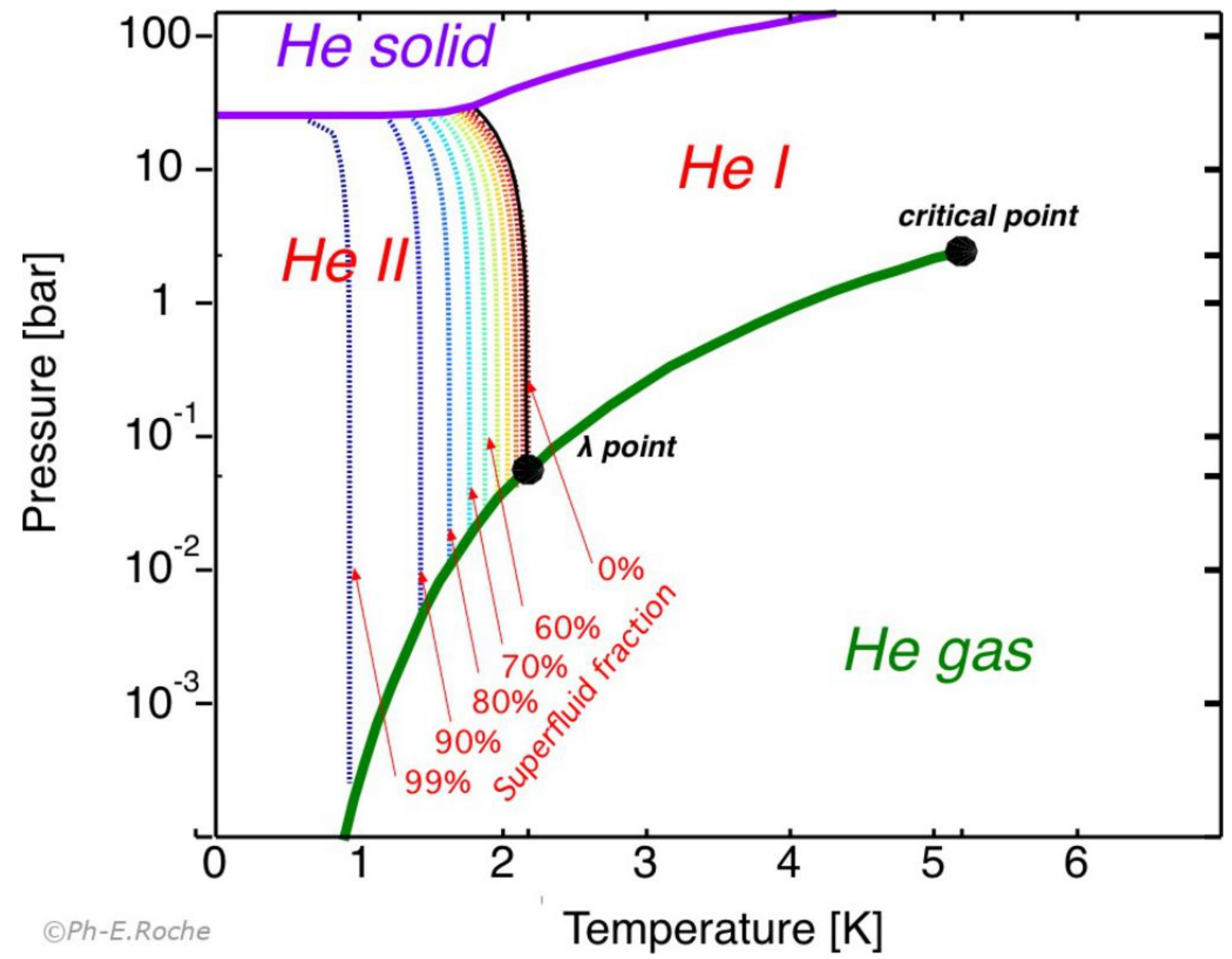


Optical phonon

Gapped

Accoustic phonon

Gapless



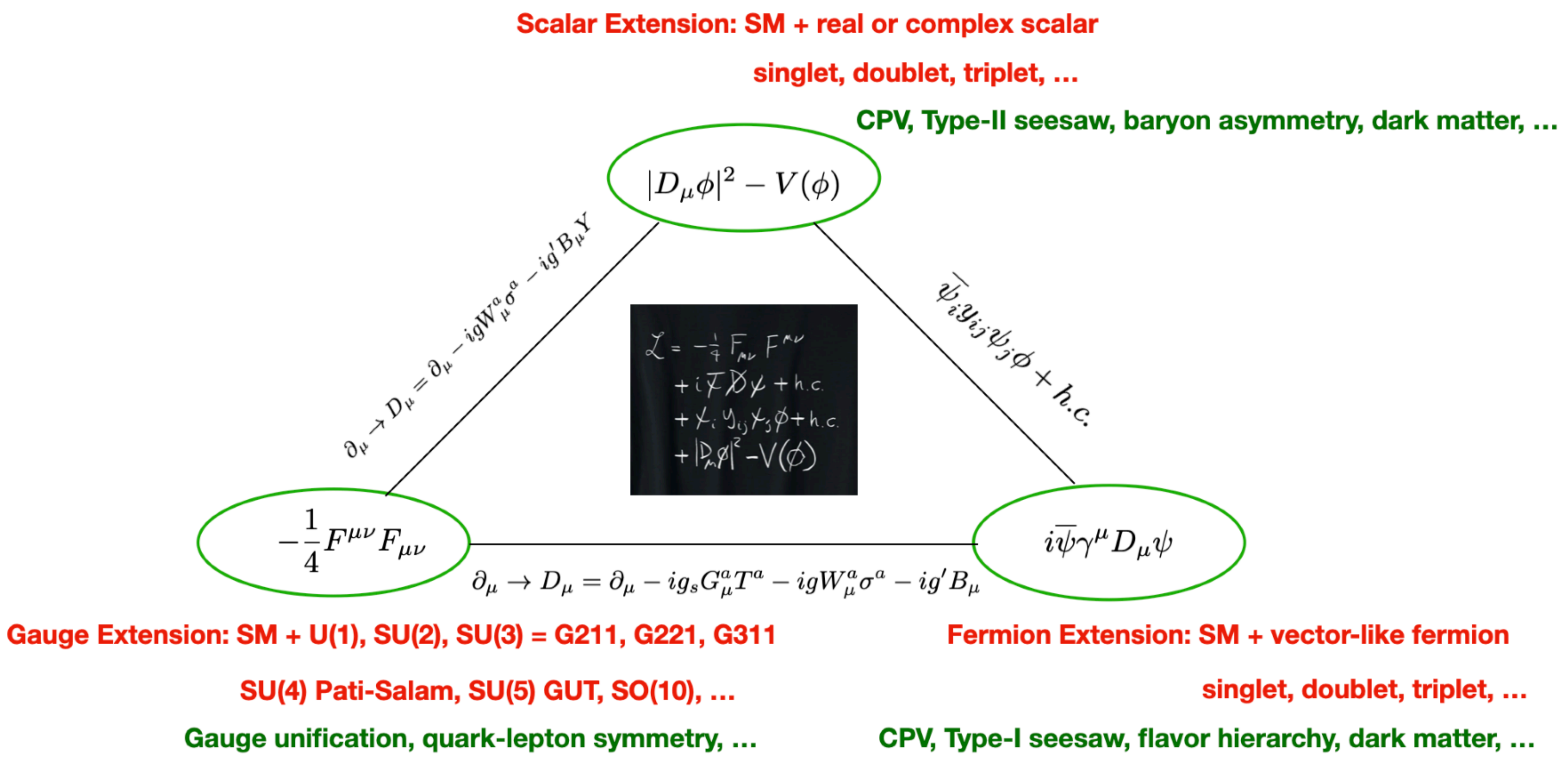
$$\nabla^i\pi^j + \nabla^j\pi^i - \dot{\pi}^i\dot{\pi}^j + \vec{\nabla}\pi^i \cdot \vec{\nabla}\pi^j$$

$$\dot{\pi} + \tfrac{1}{2}\dot{\pi}^2 - \tfrac{1}{2}(\vec{\nabla}\pi)^2$$

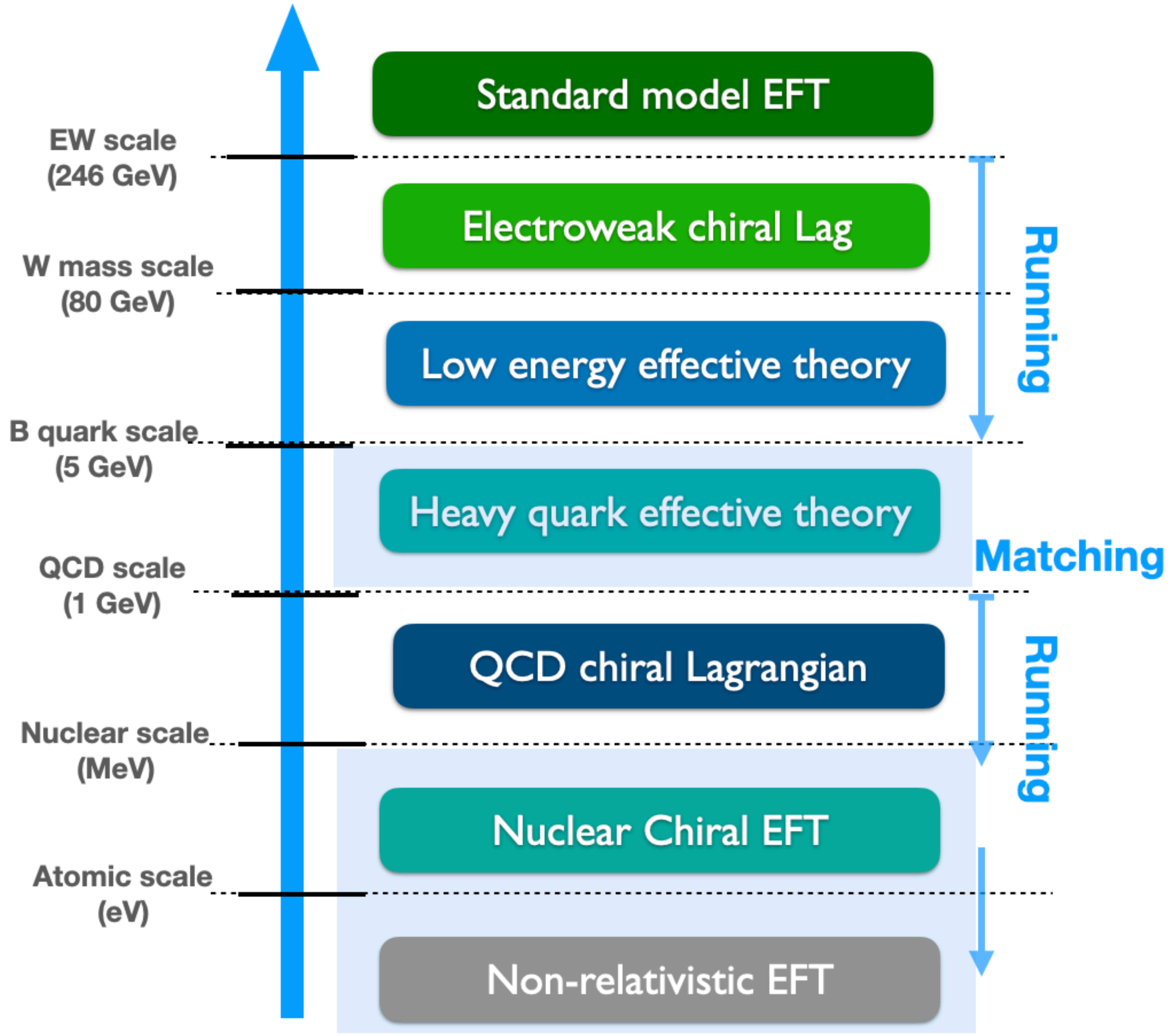
Summary and Outlook

Summary

Top-down: New physics model building



Bottom-up: New physics from EFT



Outlook

The spacetime symmetry dictates interactions

Poincare symmetry

Relativistic EFT

- Massless EFT
  - SMEFT
  - Gravity EFT
- Massive EFT
  - Weak EFT
  - Low energy EFT
- EFT without anti-particle
  - HQET
  - Heavy baryon ChPT

Goldstone

Spin symmetry

NR EFT

- NR EFT
  - Pion-less nuclear EFT
  - Spinning black hole
  - Cold atom
- NR with more modes
  - NRQCD
  - Phonon, superconducto
  - Superfluid, …

Jiang-Hao Yu (ITP-CAS)

敬祝李老师：八十载春秋风华，一辈子桃李芬芳！

Thanks for your attention!

Backup Slides

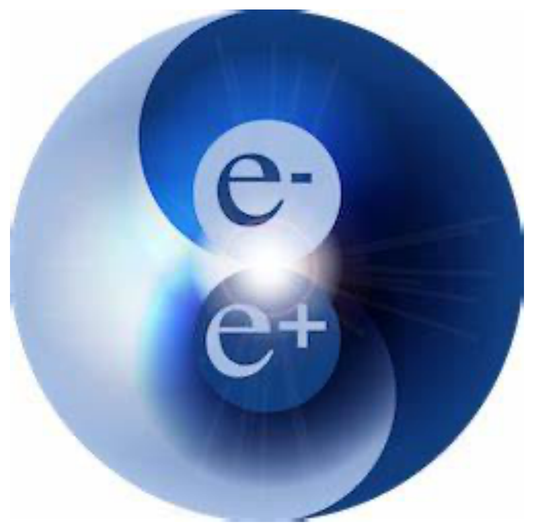
Internal space

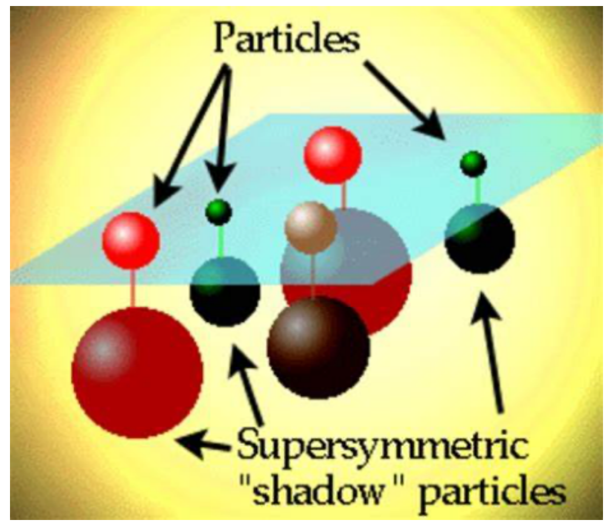
Coleman-Mandula theorem, internal space cannot mix with spacetime symmetry

[Yu-Han Ni, Chao Wu, Yi-Ning Wang, **J.H.Yu**, 2412.03762]

Superspace (Grassmann)

$\phi \longleftrightarrow \psi$





$(\lambda, \tilde{\lambda}, \eta^A)$

Internal space $\quad p_M = \{p_\mu, Q_\alpha, \bar{Q}_{\dot{\alpha}}\}$

$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu \qquad \left\{[p|^a \frac{\partial}{\partial \eta}, |p\rangle^{\dot{a}}\eta\right\} = |p\rangle^{\dot{a}}[p|^a$$

with R-charge, ISO(2)

$$Q_\alpha \to e^{-i\lambda} Q_\alpha \quad \text{and} \quad \bar{Q}_{\dot{\alpha}} \to e^{i\lambda}\bar{Q}_{\dot{\alpha}} \qquad \eta \to e^{i\lambda}\eta$$

$$[R, Q_\alpha] = -Q_\alpha \quad \text{and} \quad [R, \bar{Q}_{\dot{\alpha}}] = +\bar{Q}_{\dot{\alpha}}$$

Hyperspace (spinor)

$\lambda^I_\alpha \longleftrightarrow \tilde{\lambda}^I_{\dot{\alpha}}$

$$p_\mu,\ \lambda^I_\alpha \longrightarrow P_M = (p_\mu, m, \tilde{m}), \quad \lambda^I_A = \{\lambda^I_\alpha, \tilde{\lambda}^{\dot{\alpha}I}\}$$

ISO(2) x ISO(3,1) $\qquad (\lambda, \tilde{\lambda}, \eta, \tilde{\eta})$

Internal space

$$[m, \tilde{m}] = 0. \qquad m \equiv \frac{1}{2}\lambda_{\alpha I}\lambda^{\alpha I}, \quad \tilde{m} \equiv \frac{1}{2}\tilde{\lambda}_{\dot{\alpha} I}\tilde{\lambda}^{\dot{\alpha} I}.$$

with transversality-charge

$$m \to e^{-i\phi} m\,, \quad \tilde{m} \to e^{i\phi}\tilde{m}.$$

$$[D_-, m] = -m\,, \quad [D_-, \tilde{m}] = +\tilde{m}\,.$$

Relate to chirality

Extended Poincare Symmetry

Additional symmetry to relate and determine amplitudes

[Yu-Han Ni, Chao Wu, Yi-Ning Wang, **J.H.Yu**, 2412.03762]

$$\lambda_\alpha^I \longleftrightarrow \tilde{\lambda}_{\dot\alpha}^I$$

$$[23][31], \langle 23\rangle[31], [23]\langle 31\rangle, \langle 23\rangle\langle 31\rangle$$

U(1) charge

$$\lambda_\alpha^I \to e^{-\frac{i}{2}\phi}\lambda_\alpha^I\,, \quad \tilde{\lambda}_{\dot\alpha I} \to e^{\frac{i}{2}\phi}\tilde{\lambda}_{\dot\alpha I}.$$

$$m \to e^{-i\phi}m\,, \tilde{m} \to e^{i\phi}\tilde{m},$$

$$D_- \equiv \frac{1}{2}\left(-\lambda_\alpha^I\frac{\partial}{\partial\lambda_\alpha^I} + \tilde{\lambda}_{\dot\alpha}^I\frac{\partial}{\partial\tilde{\lambda}_{\dot\alpha}^I}\right)$$

$$[D_-, m] = -m\,, \quad [D_-, \tilde{m}] = +\tilde{m}\,, \quad [m, \tilde{m}] = 0.$$

ISO(2) x ISO(3,1)

$$p_M = (\, p_\mu \mid m \quad \tilde{m}\,)$$

Lorentz extension

$$\lambda_A^I = \{\lambda_\alpha^I, \tilde{\lambda}^{\dot\alpha I}\}$$

$$T_{\alpha\dot\alpha}^+ \equiv \tilde{\lambda}_{\dot\alpha}^I\frac{\partial}{\partial\lambda^{\alpha I}}, \quad T_{\alpha\dot\alpha}^- \equiv \lambda_\alpha^I\frac{\partial}{\partial\tilde{\lambda}^{\dot\alpha I}}$$

$$\lambda_\alpha^I \overset{T^-}{\longleftrightarrow} \tilde{\lambda}_{\dot\alpha}^I$$

$$[(T^+)_{\alpha\dot\alpha}, (T^-)_{\beta\dot\beta}] = -\frac{i}{2}(\varepsilon_{\alpha\beta}\tilde{L}_{\dot\alpha\dot\beta} + \tilde{\varepsilon}_{\dot\alpha\dot\beta}L_{\alpha\beta}) - \frac{1}{2}\varepsilon_{\alpha\beta}\tilde{\varepsilon}_{\dot\alpha\dot\beta}D_-$$

$$L_{MN} = \left(\begin{array}{c|cc} L_{\mu\nu} & T_\mu^+ + T_\mu^- & i\,(T_\mu^+ - T_\mu^-) \\ \hline T_\nu^+ + T_\nu^- & 0 & D_- \\ i\,(T_\nu^+ - T_\nu^-) & D_- & 0 \end{array}\right)$$

ISO(5,1)

$$\begin{tikzcd}
& {[23]\langle 31\rangle} \arrow[dr, "T_1^-\cdot T_2^-"] & \\
{[23][31]} \arrow[ur, "T_1^-\cdot T_3^-"] \arrow[dr, "T_1^-\cdot T_2^-"'] & & \langle 23\rangle\langle 31\rangle \\
& \langle 23\rangle[31] \arrow[ur, "T_1^-\cdot T_3^-"'] &
\end{tikzcd}$$

$$[D_-, (T^\pm)_{\alpha\dot\alpha}] = \pm(T^\pm)_{\alpha\dot\alpha},$$
$$[L_{\beta\gamma}, (T^\pm)_{\alpha\dot\alpha}] = -i\varepsilon_{\beta\alpha}(T^\pm)_{\gamma\dot\alpha} - i\varepsilon_{\gamma\alpha}(T^\pm)_{\beta\dot\alpha}.$$