TH Landscape for HE experiments

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/

❑ Instead of Introduction

- ✓ ***Observational evidence Universe mysterious substance – Dark Matter (DM)***
- ✓ ***Particle Physics of DM & Origin in early Universe*** **very little known up to now**
- ✓ **Historically, favored DM Thermal relic production**
- ✓ **DM thermalized with SM Plasma in early Universe.** ***Equilibrium?***
- ✓ **DM Relic *abundance*** **Interactions "freeze-out"**

↓ ↘

DM heavier (increasing) ***Large Interaction strength (decreasing)***

❖ $m_D < 100\ TeV$ $unitarity\ violation$

Griest –Kamionkowski (GK) bound, 1990

➢ **Cosmo FOPT may alter the expansion rate of the Universe**

➢ **Hierarchy**

Hierarchy problem?

- **HP** is a *vital gambling tool* accompanying by ***Naturalness***

Our observable Universe is readily “small” patch of large Multiverse

- “N-Naturalness” (N >> 1 SM-like sectors, “continents”)

Arkani-Hamed, Cohen, D’Agnolo, Hook, Kim, Pinner’16

- Effective couplings & masses can vary across Multiverse

- SUSY/ Warped extra dimensions remain ***central solution***

R Sundrum’25

Hierarchy

○ $M_{EW} \ll M_{GUT}, M_{Pl}$

Precedent. QCD p-composite $m_p \sim M_{Pl} e^{-O(1)/\alpha_{QCD}(M_{Pl})} \sim$ "Λ_{QCD}", $g_{QCD}(M_{Pl}) \sim O(\frac{1}{2})$

Many masses $\sim e^{-O(1)/\alpha_{BSM}}$?? $NP\ strong\ dynamics$??

- Warped space-time (5D)

exp. hierarchy

in 4D eff. TH at low E

$\sim e^{-O(1)L/R}$

5[th] dim. interval

radius of curvature

- Gaugino-mediated SUSY B (Hidden sector SUSY B)

$$\Lambda_{hid} \sim M_{Pl} e^{-O(1)/\alpha_{hid}(M_{Pl})}, \qquad m_{\tilde{g}} \sim \Lambda_{hid}^2 / M_{Pl}$$

Chacko, Luty, Nelson, Panton'99; Kaplan, Kribs, Schmaltz'99

LHC phenomenology is predominantly for superpartners:

- "Gauge-mediation-like":

$$qq \to \tilde{q}\tilde{q} \to 2\ times\ q + \gamma, Z + gravitinos$$

Q: How much will HL-LHC succeed?

Naturalness may be ***compromised*** by other sectors,
other universes, anthropic selection, etc.

R Sundrum'25

Clues may come from BB: GR waves from PT's, cosmological collider

- The absence of a solution to **HP** would be itself a rather profound discovery, even a ***hidden world,*** if established convincingly

Hidden World *(what do we know)*

Known {
Galactic Moving
Cosmic Microwave radiation

Observation in Universe (expansion) up to stars moving in galaxies can not be explained by ordinary matter

↓

HYPOTHESIS

NON-DETECTING DM **(GALAXIES ARE EMBEDDED INTO SPHERICAL HALO OF DM)**

DM: $\boldsymbol{\Omega_{DM} = 26.8 \pm 0.014}$ % *PLANCK COLLABORATION (2018)*

Ordinary matter: $\sim$ **5%** $\boldsymbol{constitutes\ only\ of\ E_{Univ}\ content}$

comprised $\geq$ $\boldsymbol{10\ elementary\ particles}$

- ***Admit:*** **DM composed of different kinds of *fundamental entities***

&

Gravitationally clustered into macroscopic "lumps" – *e.g., Boson stars to display the universality*

Hidden world

At high enough energies $Q \sim O(M)$ (**UV**, Cosmology)

the nearly conformal (matter) sector couples in the UV to the HIDDEN world through the exchange of heavy state(s), the messenger(s)

$$\begin{bmatrix} Nearly \\ conformal \end{bmatrix} \overset{heavy}{\underset{messenger(s)}{\leftrightarrow}} \begin{bmatrix} Hidden \\ world \end{bmatrix}$$

$$Below\ UV\ M: \frac{1}{M^{d-4}} O_{SM} \frac{1}{M^{d_{UV}}} O_{UV}$$ No masses allowed

Abundance of rare transitions, even the forbidden ones (in terms of SM).

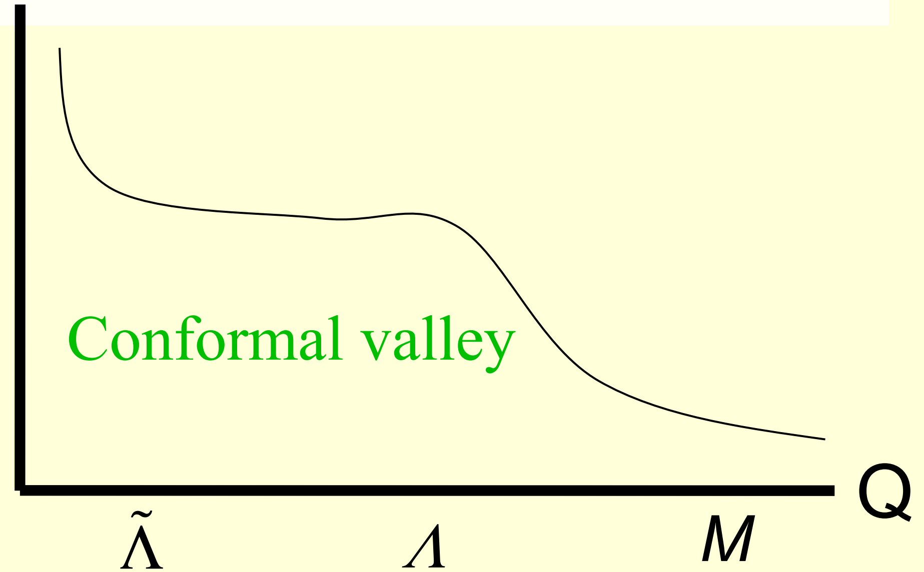
$$E.g.,\ \ H\text{-}like \to \gamma + mis.(\ DP\ ).$$

Phenomenology. Hidden & SM sectors.

NP is seen only in nearly conformal sector where

$$Q \sim \sqrt{s} \geq \tilde{\Lambda}$$

Below $\tilde{\Lambda}$ hidden sector becomes a SM particle sector.



E.g., DP: the mixing strength

$$\varepsilon = \left(\frac{\sqrt{s}}{M}\right)^{2(d-4)} \left(\frac{\sqrt{s}}{\Lambda}\right)^{2d_{IR}} \left(\frac{\Lambda}{M}\right)^{2d_{UV}}$$

GK'16

Q.

What is TH possibilities are relevant for current & future experiments?

➢ TH **landscape** to ***LHC***

Precision ← SM → ***Higgs***

QCD

↓

Beyond SM

↙ ↘

Composite Higgs

DM ↘

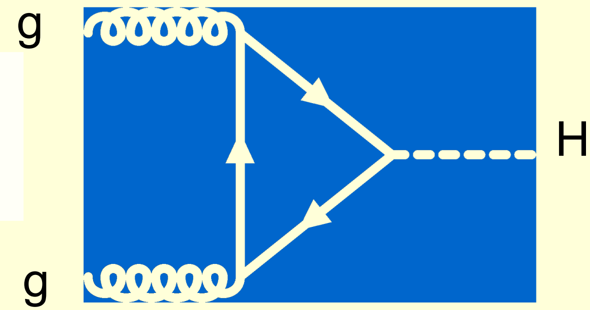
↓ ↓ exotics

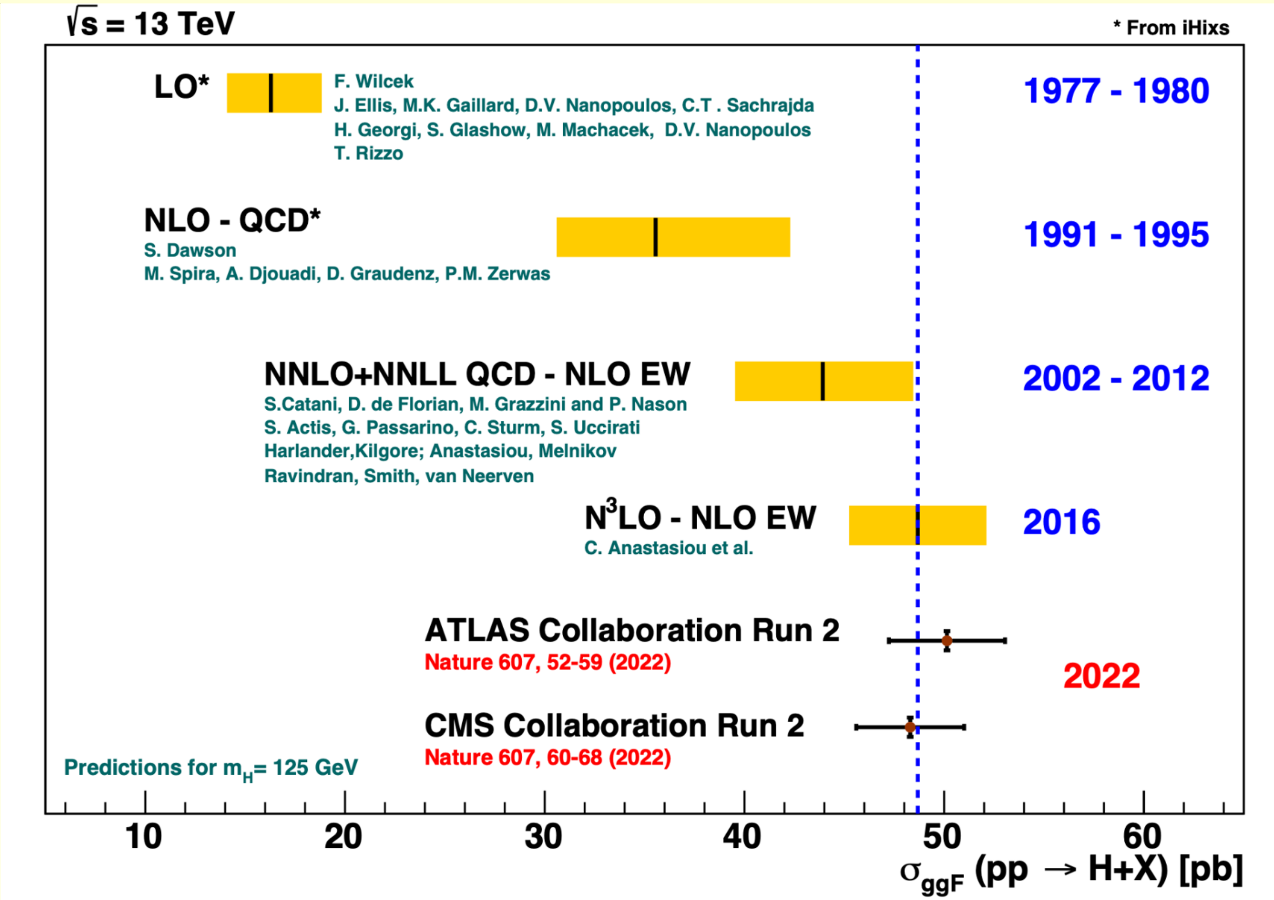
ν mass

Extra dim.

- Theorists not fully replaceable yet

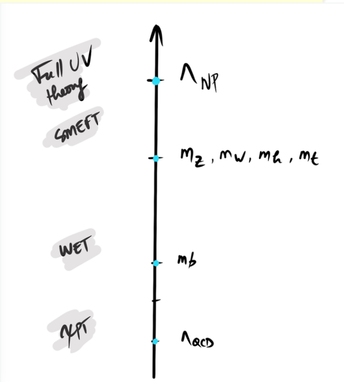
TH Higgs production progress in σ_{ggH} *vs time* $(1977 - today)$

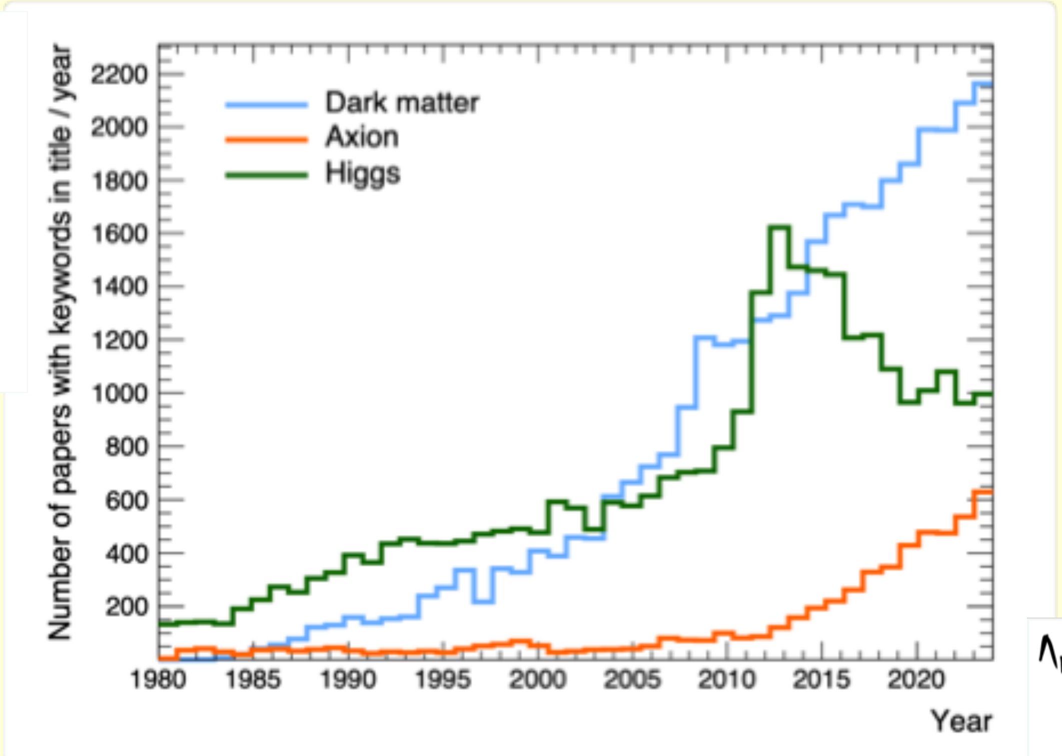




TH & EXP landscape 1980-2025 …..

Search for ***NP*** is a global effort ***spanning*** PP, Cosmology, Astrophysics





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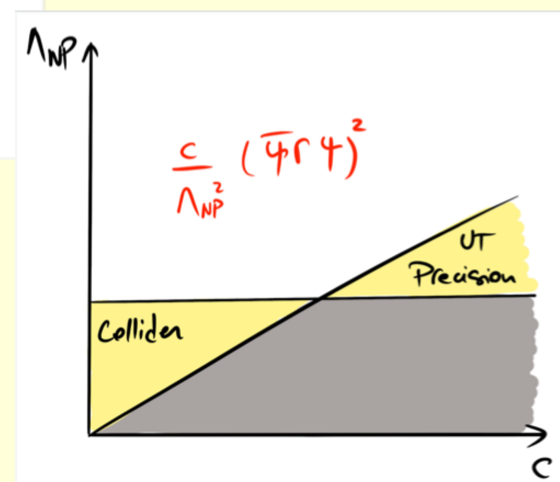


Candidates to DM

- Dark photon $\overline{\boldsymbol{\gamma}}$,

$\boldsymbol{\varepsilon}\ (\overline{\boldsymbol{\gamma}} - \gamma\ kinetic\ mixing)\ ,\quad m_{\overline{\boldsymbol{\gamma}}} < 1\ GeV$

- **Dark fermion** $\bar{f}$, “Darkonium”, $e^+e^- \to \gamma\ \Upsilon_D \to \gamma\ \overline{\gamma}\ \overline{\gamma}\ \overline{\gamma}$

$\mathbf{0.05} < m_{\Upsilon_D} < \mathbf{9.5}\ GeV,\qquad \mathbf{0.001} < m_{\overline{\gamma}} < \mathbf{3.16}\ GeV,$

BABAR (2022)

Dark matter Nature (Unknown)

DM: ***NO INTERACTION with EM sector***
- ***No radiation***
- ***No absorption***
- ***No scattering***

❖ ***DM exploration:***
- ***DM production at accelerators, lifetime ??***
- ***DM interaction with baryonic matter portal?***
- ***Matter detection*** $\begin{cases} \boldsymbol{annihilation\ of\ DM} \\ \boldsymbol{decays\ of\ DM} \end{cases}$

○ ***What/*****where** ***is a SYMMETRY/*** **are the SYMMETRIES** ***?***

❖ Conformal symmetry

Max. space-time group symmetry *(SUSY no considered)*

SSB: $G_{conf}(d) \times G_{int} \to \Pi$ $(vector\ subgroups\ of\ x_\mu\ \&\ internal\ symmetries)$

$$factor\ space:\ \boldsymbol{g_{conf}} = \boldsymbol{e^{ix_\mu P^\mu}}\quad \boldsymbol{e^{iB_\mu(x)K^\mu}}\quad \boldsymbol{e^{iD\phi(x)}}$$

translations SCT Dilatation

Hidden scalar DM, field $\boldsymbol{\phi}$ with $\langle\phi\rangle \neq 0$ $breaks\ conformal\ invariance\ at\ f > v$

$\widehat{D}\phi = d_\phi\phi,\ \widehat{K_\mu}\phi = 2x_\mu d_\phi\phi$ **No direct action of SCT on hidden field $\boldsymbol{\phi}$.** $\boldsymbol{Through\ x_\mu\ only}$!

- **Vector field** $\boldsymbol{B_\mu(x)}$ $not\ necessary\ to\ describe\ any\ local\ fluctuations\ in\ vacuum$

$B_\mu(x) \sim f^{-1}\partial_\mu\phi(x)$ ***Dark Photon*** *field massive* *Non-primary operator*

GK'19

- ***Dark Photons*: Fixed Target vs Colliders search**

$$L_{int} = \sum_{k,l,m,n}^{k+l+m=n+4} \frac{O_{DM}^{(k)} \; O_{DP}^{(l)} \; O_{SM}^{(m)}}{\Lambda^n}$$

O_{DP}: $B_{\mu\nu}$ ***mediator vector operator*** / *Portal* *to DM*

- $O_{SM}: H^+H,\ O_{DM}: S^2,\ O_{DP}: B_{\mu\nu}$

LHC today
$2.2 \times 10^{34}\ cm^{-2}s^{-1}$
1.6×10^{11} ppb
$\beta^* = 60/18$ cm
110-120 fb^{-1}/year

$$LLP\ (s) \to \gamma\bar{\gamma} \to \gamma l\bar{l}(\nu\bar{\nu}), \ldots.$$

- Production cross section $\sigma \sim \epsilon^2 \frac{\zeta^2}{E^2} \left(\frac{E}{\Lambda}\right)^{2n}$

HL-LHC
$5 \times 10^{34}\ cm^{-2}s^{-1}$
2.2×10^{11} ppb
$\beta^* = 15$ cm
300 fb^{-1}/year

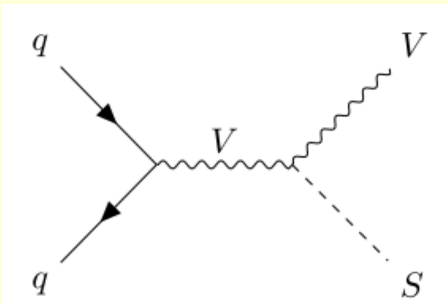
$$R_{FT/Coll} = \frac{N_{FT}}{N_{Coll}} = \frac{L_{FT}}{L_{Coll}} \left(\frac{E_{FT}}{E_{Coll}}\right)^{2n-2} = \begin{cases} 10^{+4}, n = 1 \\ 10^{-2}, n = 2 \end{cases} \text{SPS/LHC}$$

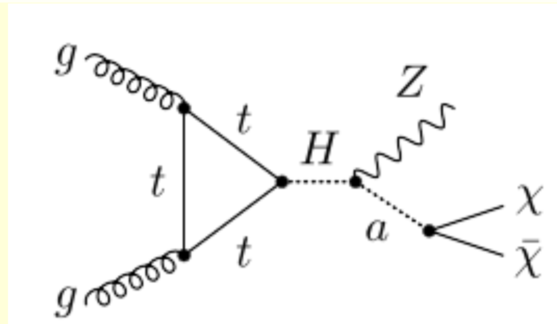
$$\begin{cases} 10^{+3}, n = 1 \\ 10^{-3}, n = 2 \end{cases} \text{SPS/}\mathbf{HL\text{-}LHC}$$

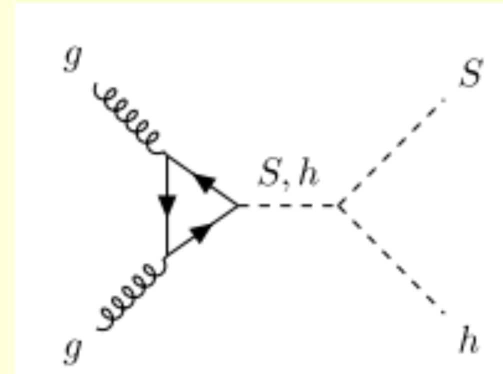
❑ Earth laboratory: *Search for Dark Matter Candidates*

The presence of DM can only be revealed by an imbalance in the transverse momentum in the detector measured as missing transverse momentum

An effective approach to DM within the *LHC Dark Matter Forum, ATLAS & CMS*

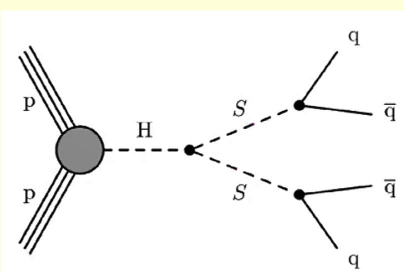


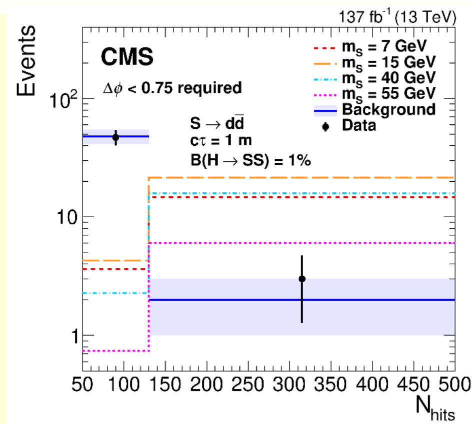


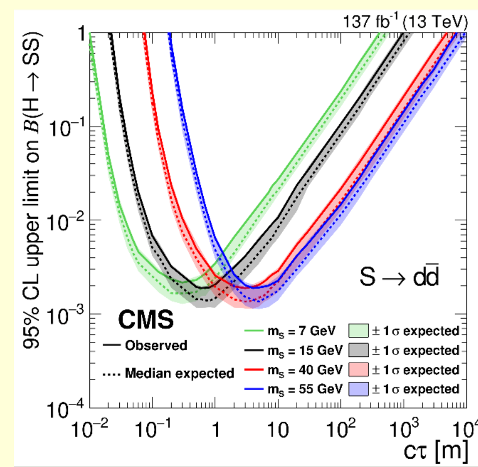


This exciting tool opens up a new program of searches for *LLPs* (Scalar DM, S) in a wide variety of theoretical models

$$h \rightarrow SS \rightarrow 4l \text{ or } 4q$$







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❑ By **Conformal inv.**, the β – functions for ALL states (CFT + SM) **vanish.**

If $\left.\begin{matrix} QCD \\ EM \end{matrix}\right\} \in conformal\ sector \rightarrow \sum_{light} b_o = -\sum_{heavy} b_o\ (Higgs)$

quark-lepton conformal condition

➢ **The** ***hidden s- scalar mass*** **splits** ***light*** **and** ***heavy (q's & l's)*** **states !**

$$\frac{\beta(g)}{2g}\left(G^a_{\mu\nu}\right)^2 \rightarrow \frac{\alpha_s}{8\pi} b_o^{light}\left(G^a_{\mu\nu}\right)^2, \qquad b_o^{light} = -11 + \frac{2}{3} n_L$$

$$m_s \sim O(\Lambda) \rightarrow n_L = 3{:}\ \ COUPLING\ STRENGTH \sim \frac{ggs}{ggh} \sim \mathbf{14}!\ increase$$

➢ **Primary photons emission:**

$-8/3$ ↰

$$\Gamma(s \rightarrow \gamma\gamma) \cong \left(\frac{\alpha F_{anom}}{4\pi}\right)^2 \frac{m_s^3}{16\pi f^2}, \quad F_{anom} = -\left(\frac{2n_L}{3}\right)\left(\frac{b_{EM}}{b_0^{light}}\right)$$

❑ *Primary photons. Observation.*

S unstable, showers of $\gamma\gamma,\ \bar{\gamma}\bar{\gamma},\ \bar{\gamma}\gamma, \ldots$ $(conformal\ EM\ anomaly)$

- **Measurement of $\gamma' s$ *escape* $-$ *decisive way to observe* & *differentiate* primary $\gamma' s$ and** *ordinary* $\gamma' s$ $(\pi^0 \to \gamma\gamma, \ldots)$

- **Fluctuation rate of *primary* $\gamma' s$ *production in approximate conformal sector* (*proximity to PT*)** $f \sim O(\Lambda), f_\pi \approx 0.3\Lambda$

$$r_{\gamma\gamma} = 1 + \frac{BR(\pi^0 \to \gamma\gamma)}{BR(s \to \gamma\gamma)} = 1 + m_\pi^3 \left(\frac{6}{F_{anom}}\right)^2 \xi^3$$

❑ Abundant $\gamma' s$ *escape*: $r_{\gamma\gamma} \to \infty$ *as* $\xi(T \to T_c) \to \infty$ *GK'2022*

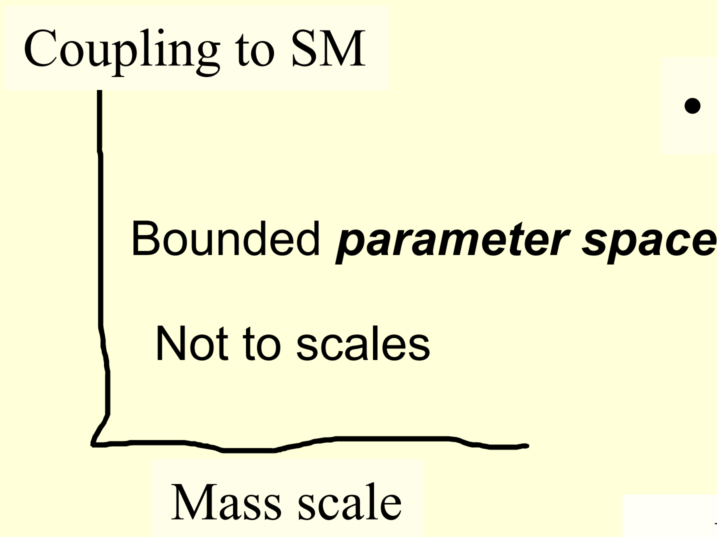
with $n_L \to 0$, $and\ N_f \to N_f^c,\ m_s \approx \left(1 - \frac{N_f}{N_f^c}\right)^{\frac{1}{2}} \Lambda$

- N_f^c separates ***conformal phase*** from the one with the ***chiral symmetry***

Q.

➢ Where can NP live?

➢ What can the LHC cover ?



- Seems like a ***daunting parameter space***

- Structure of QFT or Gauge theories allows ***seclusion*** from the SM easily

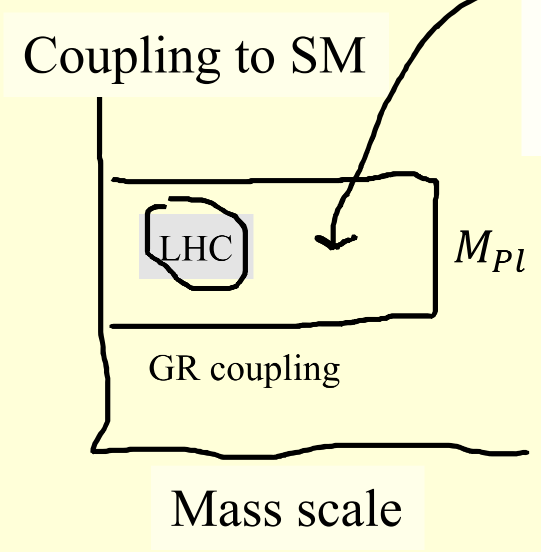
  - Discrete choices of symmetries & charges
  - Decoupling

- Portal interactions can be large or even quite small enough

Q.

➢ Where does the LHC live?

- This ***TH landscape*** is too big to be useful for LHC, but important to keep in mind



One has to think about other results of other experiments
or
planning future experiments

What shall we have

HiLumi
HL-LHC PROJECT

FCC
hh ee he

clic

International
MUON Collider
Collaboration

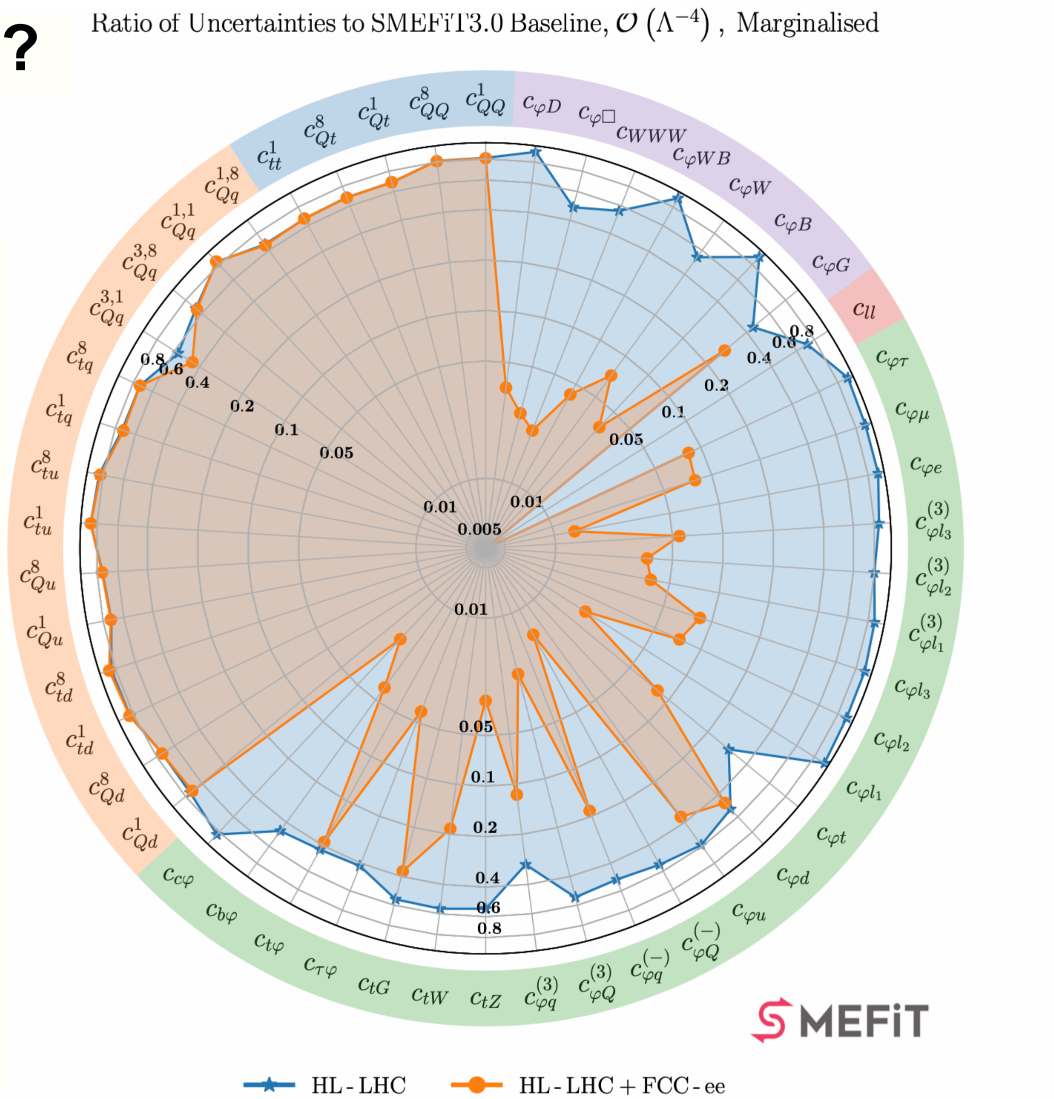
CEPC

ilc
international linear collider

Linear Collider Vision

What'll the FCC-ee measure?

- EW @ the Z-pole
- Light fermion pair production
- Higgsstrahlung & VBF
- W boson pair production
- Top-quark pair production
- PS "Toponium" (343 GeV ?)
- ……..



2206.08326

Celada et al. 2402.12809

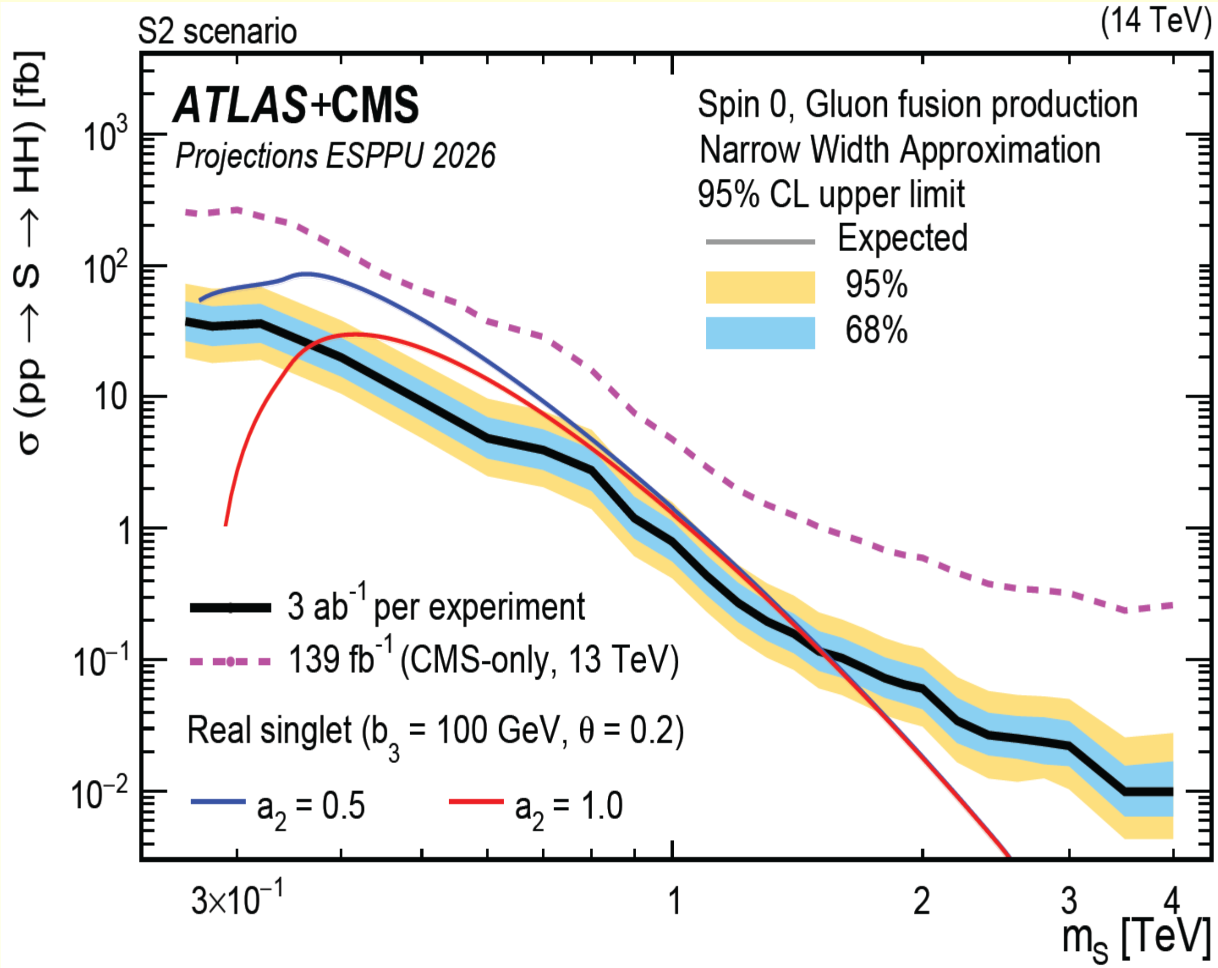
Higgs physics. Perspectives ?

Model	What is it good for?	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^{\pm}$ and Z bosons Yukawa couplings generate fermion masses	H_{SM}
SM + real singlet	Can give CDM or EWK baryogenesis, but not both…	h, H
SM + complex singlet	Can give both CDM and EWK baryogenesis, …	h, H, A
SM + complex doublet e.g., MSSM	2HDM, prerequisite for SUSY, natural in GUT additional source of CP violation, Higgs-sector CDM	h, H, A, $H^{\pm}$
SM + complex doublet + complex singlet e.g., nMSSM	resolves the μ-problem in MSSM h(125) is unnaturally heavy in MSSM – not in nMSSM	h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
SM + triplet e.g., Georgi-Machacek model	gives a natural explanation for small neutrino masses	h, H, A, $H^{\pm}$, $H^{\pm\pm}$

- **Every model contains SM h(125)!** **Must be consistent with LHC observables**

- **Outlook to HL-LHC**

Expected upper limits on a **generic gg->S->HH**
Overlayed: Real scalar singlet extension of the SM



ATL-PHYS-PUB-2025-018

$$V(\Phi,S) = -\mu_H^2|\Phi|^2 + \lambda_H|\Phi|^4 + b_1 S - \frac{\mu_S^2}{2}S^2 + \frac{b_4}{4}S^4 + \frac{a_2}{2}|\Phi|^2S^2 + \frac{b_3}{3}S^3 + \frac{a_1}{2}|\Phi|^2 S$$

▪ Results

Null results can carry significant information depending on the **context**

Lack of curiosity: it's just the SM (Higgs)

More general: bound on the scale of NP

$$\frac{1}{\Lambda^2} H^2 \mathcal{O}_{SM} \rightarrowtail \delta\kappa \sim \frac{v^2}{\Lambda^2} \Rightarrow \Lambda \geq TeV$$

Once you care about **naturalness**,
you care about explaining **the scale** as well

e.g., EFT: Power Counting from Operator Dimensions

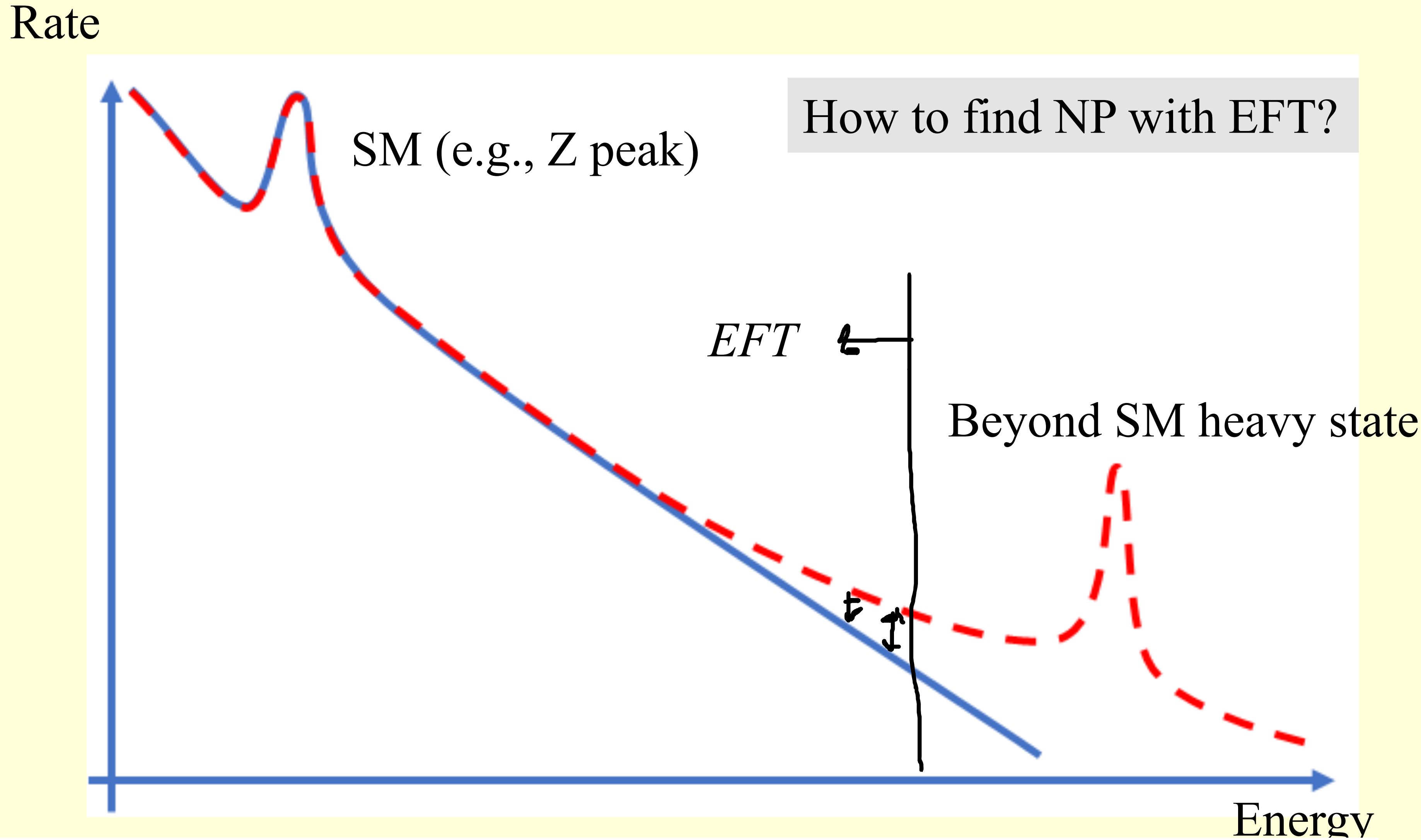
Flavor

$$\frac{c_q}{\Lambda^2} q_1 \overline{q_2} q_1 \overline{q_2} \rightarrow \boldsymbol{\Lambda \geq 10^3 - 10^4\ TeV}, q_i = u, d, s, b$$

EWPT

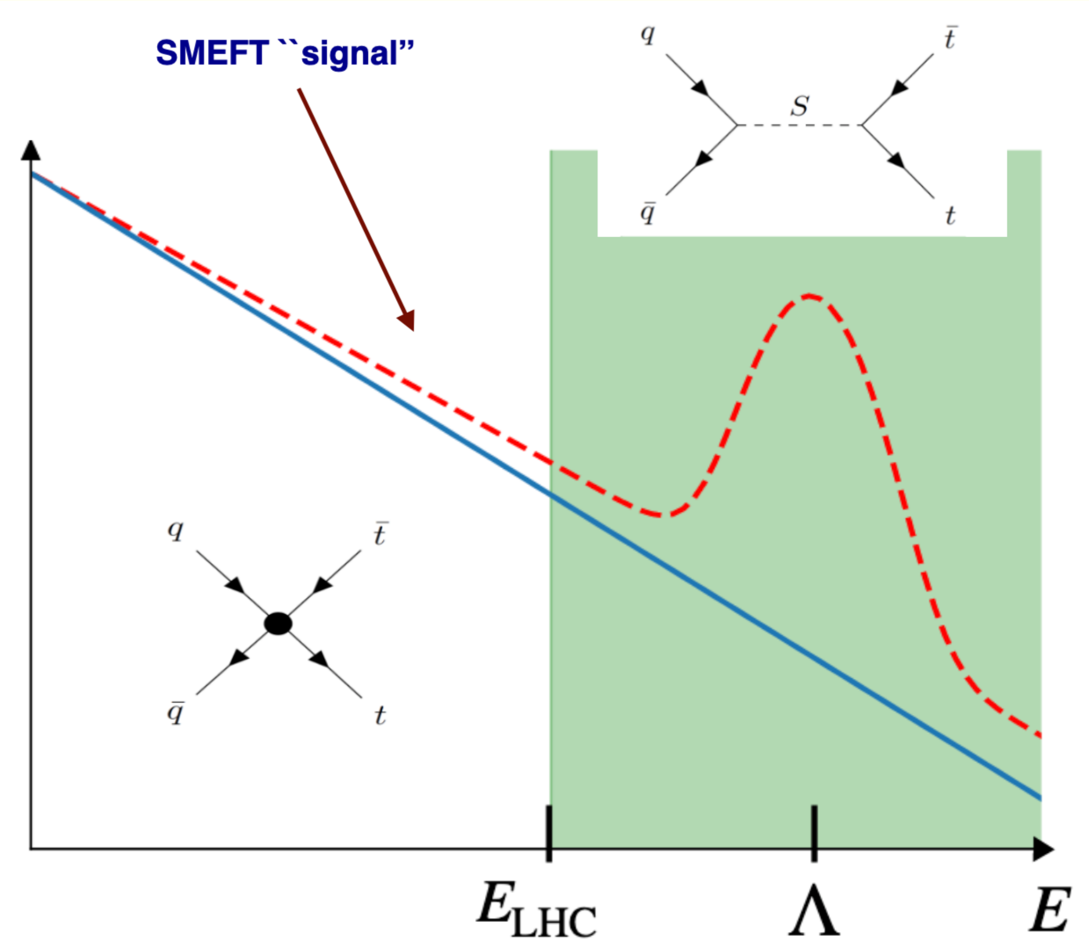
$$\frac{c_H}{\Lambda^2} \left(H^+ D_\mu H\right)^2 \rightarrow \boldsymbol{\Lambda \geq 10\ TeV}$$

EFT Logic



The way to probe NP beyond the direct LHC energy reach

SMEFT



$$L_{SMEFT} = L_{SM} + \sum_{d}^{N} \sum_{j \in O^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} O_j^{(d)}$$

▪ EFT & HEP

Energy

Λ

$NP\ particles, DM \qquad L_{NP}(\phi,\psi,V,\ldots;\underbrace{\boldsymbol{\phi}',\boldsymbol{\psi}',\boldsymbol{V}',\ldots}_{new\ heavy})$

$\downarrow$

$EFT \qquad L_{SM}(\phi,\ldots) + L_{\dim 6}(\phi,\ldots)$

SM $\quad L_{SM}(\phi,\ldots)$

$$L_{EFT} = L_{SM} + \Lambda^{-2}\sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + O(\Lambda^{-4})$$

Dim-6: 59 operators

Buchmuller, Wyler'86

NP Pathway through the Observables ϵ_n

$$\Delta\epsilon_n = \epsilon_n^{exp} - \epsilon_n^{SM} = \frac{1}{\Lambda^2}\sum_i c_i^{(6)}(\boldsymbol{\mu})\,\alpha_{n.i}^{(6)}(\boldsymbol{\mu}) + O\left(\frac{1}{\Lambda^4}\right)$$

Precise exp. meas'nts

Precise SM predictions

Precise EFT predictions

Q.: How about this $\boldsymbol{\mu}$?

Does this matter?

(Super)HEP is revealed by EFT through the HE collider precise measurements (SM)

○ More powerful

New way to organize searches based on what's measurable

$$\boldsymbol{\varepsilon} \leftrightarrow SM + \frac{\lambda_i}{\Lambda^{\Delta_i - 4}} \mathcal{O}_i$$

↓

Fractional uncertainty on measurement

- For a given $\boldsymbol{\varepsilon}$ what's the $\boldsymbol{\Lambda}$?

$$\Lambda = E\left(\frac{\lambda_i}{\varepsilon}\right)^{1/\delta_i} \qquad \Lambda = v\left(\frac{\lambda_i}{\varepsilon}\right)^{1/\delta_i}$$

- *For the Higgs LHC*: assuming $\lambda_i \sim O(1)(tree - level\ NP)$, good precision $\boldsymbol{\varepsilon} \sim 1\%, \delta_i = 2\ should\ dominate$.

Then, $\boldsymbol{\Lambda \approx 2.5\ TeV}$

○ **More powerful**

Tree-level:
LHC is not in the decoupling regime,
thus tree-level is what matters generically

- For E- LHC

$$\Lambda = E\left(\frac{\lambda_i}{\varepsilon}\right)^{1/\delta_i}$$

- Assuming $\lambda_i \sim O(1)$, $\varepsilon \sim 1\%$, $\delta_i = 2$, $E \sim 10\, TeV$, then, $\boldsymbol{\Lambda \approx 100\, TeV}$

Sometimes: Don’t listen to theorists too much, or just the right theorists /S. Weinberg/

LHC: DP experimental signature

✓ Experimental signature of events $h \to \gamma\bar{\gamma}$ from invisible decays $\bar{\gamma} \to \bar{\nu}\nu$ or $\bar{\gamma} \to \bar{\chi}\chi$ would be clean and the later can be selected with small BGR due to excellent capabilities of ATLAS and CMS for precise identification and measurements of initial Higgs state

➢ **Strategy of the analysis:** identify $\bar{\gamma} \to inv$ candidates by precise reconstruction of the initial Higgs state

- The ***measured rate*** of such events has to be compared to that expected from known sources.

Signal

- ❑ Overall signal strength $gg \to h \to \gamma\bar{\gamma}$

$$BR(h \to \gamma\bar{\gamma}) \approx (1 + a\varepsilon^2\Omega)BR^{SM}(h \to \gamma\gamma),\ \Omega = (1 - \frac{m_{\bar{\gamma}}^2}{m_h^2})^3$$

- Salient feature: $\bar{\gamma}$ energy with continuous spectrum vs $h \to \gamma\gamma$

- *By measuring* E_γ *spectrum in* $h \to \gamma\gamma$:

  discriminate the presence of DP or not

- o DP signal (exp. signature): detected in missing E & p distribution

Once DP produced/observed:
E_γ *spectrum* is NO more $\delta -$ *distribution peaked* @ ~ 0.5 m_h,
but rather continuous with $E_\gamma = [0, 0.5\, m_h]$

❖ Dark photons. Observations.

- $\mathbf{s} \to \gamma\bar{\gamma} \to \gamma l\bar{l}, \sim C_A\,\Lambda^{1-d}\,\bar{l}\,\gamma^{\mu}\gamma^{5} l\,\partial_{\mu} s,$

  $\gamma - \bar{\gamma}\ interference, \ \sim\varepsilon^{2}\ mixing$

Lifetime $\bar{\gamma}$, $\tau_{\bar{\gamma}} \sim \left(\frac{\Lambda}{\tilde{\mu}}\right)^{2(d-1)} \frac{1}{C_A^2\,\varepsilon^2\,\tilde{\mu}}$ *mean displacement of the vertex*

GK'21

- $\tau_{\bar{\gamma}} \geq 10^{+8} sec\,!$, $if\ \ d \to 2,\ \ C_A \sim O(1),\ \ \Lambda \sim O\left(M_{pl} \sim 10^{19}\ GeV\right)$

Candidate to DM *(almost stable)*

Exp. Constraints ↷

BABAR **(2017) &** ***NA64 (2019)*** $\varepsilon\ \leq\ 10^{-3}\ \ \tilde{\mu} \leq 8\ GeV$

$\tau_{\bar{\gamma}} \geq\ 10^{+8} sec$ Compared to $\tau_{Univ.recomb.} \sim 10^{+13} sec$

Upper limit on DP mass

$$Am\left(\gamma^* \to \nu\bar{\nu}\right) = \frac{1}{2} f_\nu \bar{\nu}\left(g_{V_\nu}\gamma_\beta + g_{A_\nu}\gamma_\beta\gamma_5\right)\nu\gamma^*_\beta$$

$$f_\nu^2 = 4\sqrt{2}Gm^2, \quad G \sim 10^{-5}GeV^{-2}$$

No final state interactions: (partial decay width)

$$\Gamma\left(\gamma^* \to \nu\bar{\nu}\right) = \frac{2}{3}\bar{\alpha}\cdot\varepsilon^2 m$$

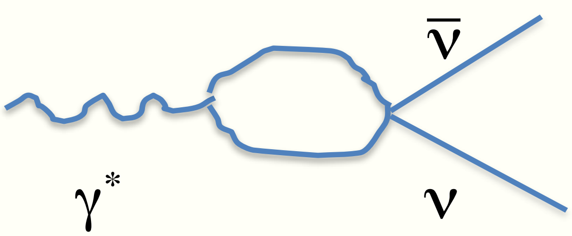
GK’16

$$\downarrow$$

$$\frac{\sqrt{2}Gg_\nu^2 m^2}{4\pi\bar{\alpha}}, \quad g^2_{V_\nu} = g^2_{A_\nu} = g^2_\nu = \frac{1}{4}$$

For $\varepsilon < 3\cdot 10^{-2} \to \boldsymbol{m < 3.3\ GeV}$

To predict m, the more detailed calculations need

E.g., EMNFF 

$$\Gamma\left(\gamma^* \to \nu\bar{\nu}\right) \sim \alpha^2 m^5 G^2 \left(ln\frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6} \right)^2$$

DP mass: Combined calculations give

$$m \approx m_\mu \sqrt{\left[\frac{3\sqrt{2}\pi\alpha^{-1}}{\sum_{l:e,\mu}\left(ln\frac{\Lambda_\nu^2}{m_l^2} - \frac{1}{6}\right)}\right]} \to m = 0.83\ GeV \qquad e, \mu\ loops$$

GK'16

$$\Lambda_\nu \sim O(m_Z),\ \varepsilon = 7.6 \cdot 10^{-3}$$

❖Dark Photon. Registration

$gg \to s \to \gamma\gamma, \gamma\bar{\gamma}, \bar{\gamma}\bar{\gamma}$ $\quad \left(\frac{33}{2} - n_L\right) \sim O(10)$ Compared to that of the $gg \to H$

$g^2_{s\gamma\gamma} \sim 10^{-10}$

GK, 2021

$$\textit{For exp.}: \; \Gamma_{\gamma\gamma} = 2\left(\frac{\mu}{8\pi}\right)^3 \left(\frac{\alpha b_{EM}}{f}\right)^2 \leq [0.013 - 0.24]\; KeV$$

$b_{EM} = -\frac{80}{9}, \quad \mu < 2m_W, \quad \sim [60 - 160]\; GeV$

$f \geq 3\; TeV$

$LHC \begin{cases} di - jets \\ di - photons \end{cases}$

For exp.: rate $\sim \varepsilon^2$: $\bar{\gamma} \to l\bar{l}$ $\qquad$ ($l: e, \mu$ <– DPs contribution)

$$\Gamma_{\bar{\gamma}l\bar{l}} = \frac{1}{3}\alpha m \varepsilon^2 \left[1 - \left(\frac{2m_l}{m}\right)^2\right]^{1/2} \left[1 + 2\left(\frac{m_l}{m}\right)^2\right]$$

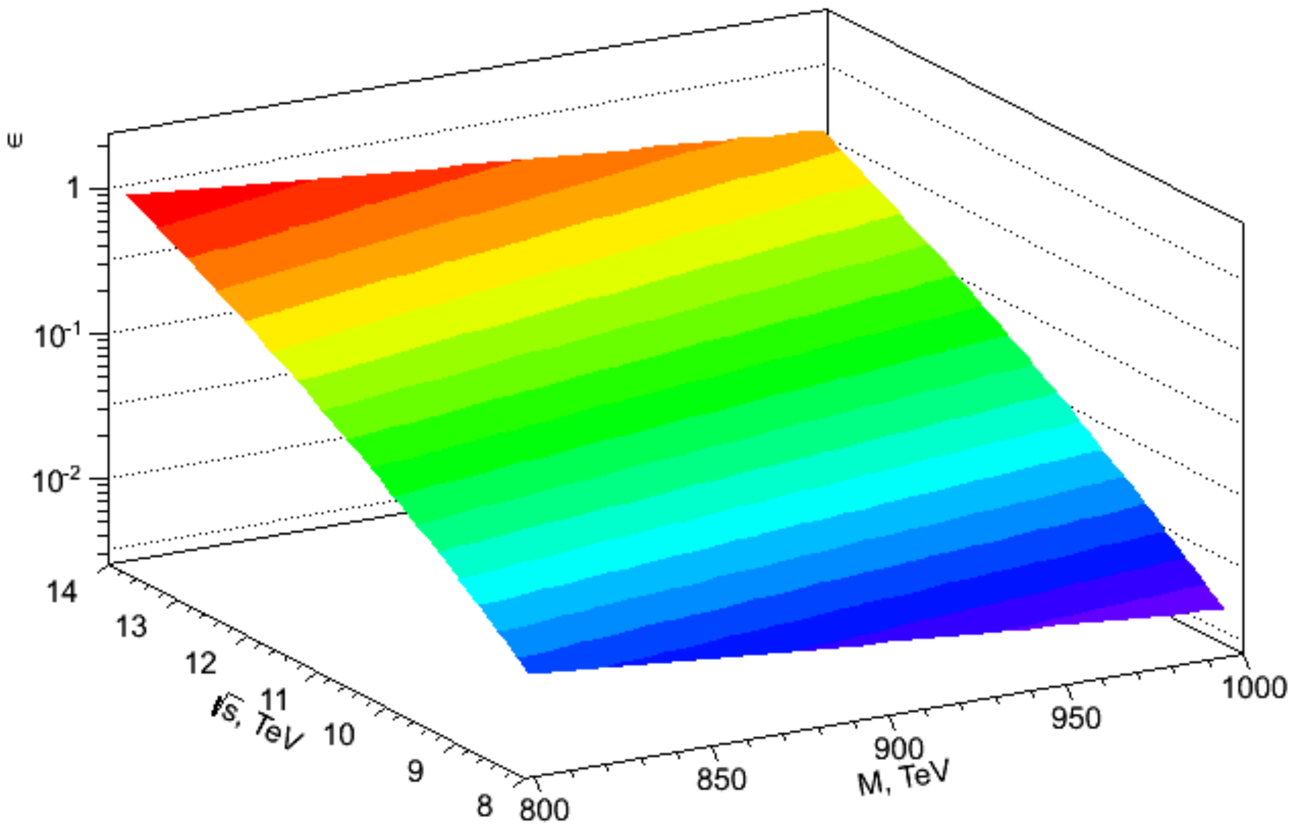
TH. $m > 2m_l, \quad \varepsilon < 3 \cdot 10^{-2}$ $\quad GK2016$ $\qquad (\varepsilon^{exp} \leq 10^{-3}),$

TH. $m < 3.3\; GeV$ $\quad \ldots \quad$ $(m^{exp} \leq 8\; GeV)$

Effect of DM sector on observable(s)

- **Mixing strength ε is bounded by** $\varepsilon < \dfrac{s^d}{\left(v^2 M^{d-2}\right)^2}$

$\sqrt{s} = 8-14\ TeV,\ \ M = 800-1000\ TeV,\ \ d = 4$



GK, 2016

❖ *Dark Photon. NO registration*

- If NO excess found → $bounds\ on\ \boldsymbol{\varepsilon} - \boldsymbol{mixing}$,

$$\boldsymbol{\varepsilon}(m, \mu)$$

- **Bright application: KOTO exp. anomaly:**

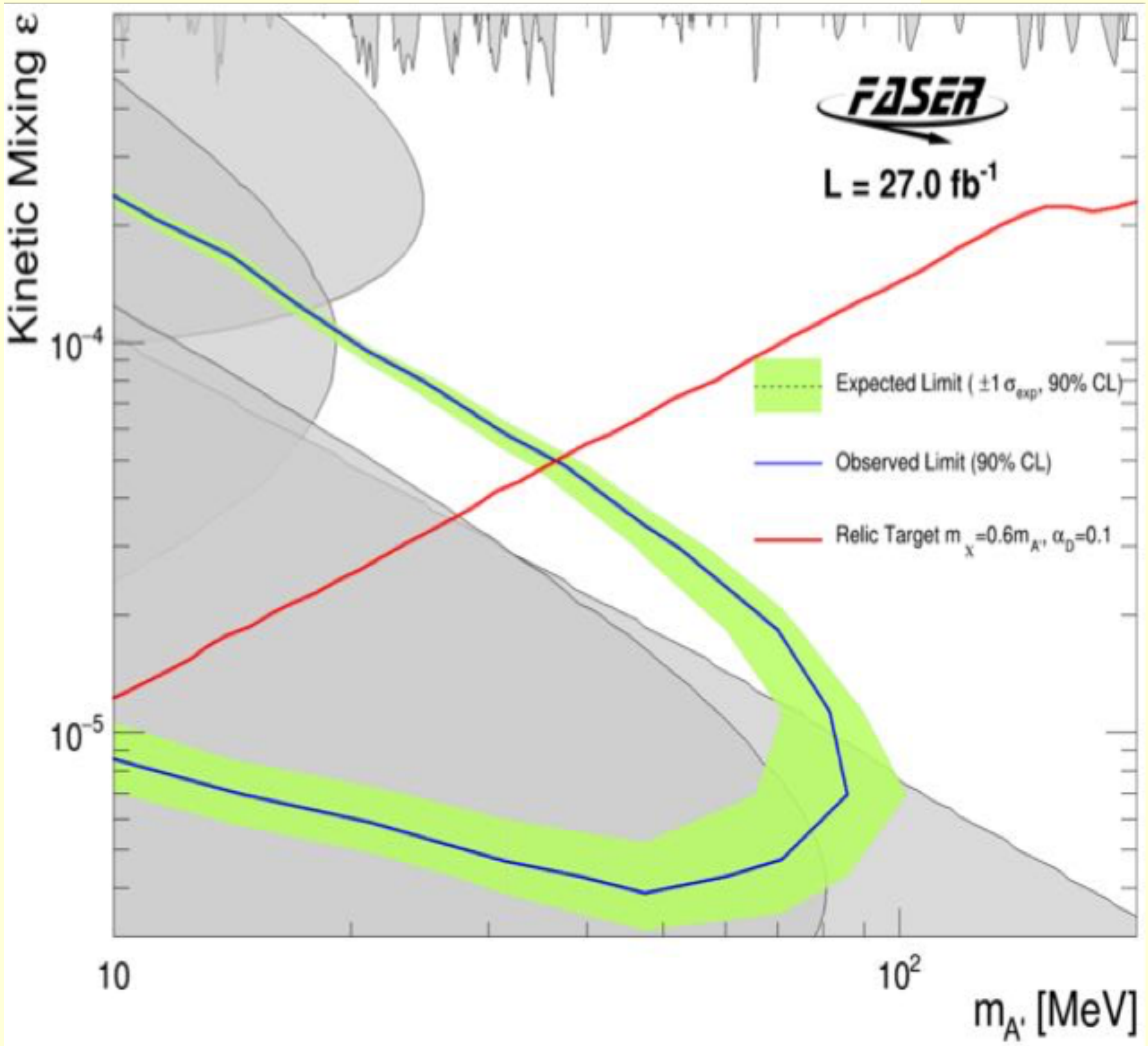
✓ $\boldsymbol{K_L \rightarrow \pi^0 \nu\bar{\nu}\ observed\ excess}$:

$\boldsymbol{due\ to\ s - scalar\ (LLP)\ missing\ energy}$,

$$\boldsymbol{K_L \rightarrow \pi^0 (LLP) \rightarrow \pi^0 \nu\bar{\nu}}.$$

$Shinohara, Egana - Ugrinovich, 2020$

Dark photons



FASER, 2308.05587

$$pp \to ATLAS\ IP \to (480\ m)\ light\ LLPs \to e^+e^-$$

No observed from 2022

Search for more scalars. Why?

1. They might be there!
2. ***2HDM*** + ***s*** can provide a Higgs-portal DM candidate
3. Warped extra dimensions predict new ***s*****.**
4. The observed B-asymmetry needs some thing:
   - New scalars at close to EW scale could drive it.
5. No convincing hints of new direction yet, however, ~ 4.2 sigma could become a discovery
6. The model space is vast.

   Well motivated models are still untried.

LHC is well placed to test them and doing so.

Scalars. Three groups

Low mass	SM Higgs (125 GeV)	High mass
$pp \to a$	$h\ rare\ decays$	$pp \to H, A$ $pp \to H^{\pm}$
$h \to aa, a_1 a_2$	$h\ \ exotic\ decays$	$H \to hh$
$h \to Za$	$h \to invisible$	$H \to sh, ss$ $A \to ZH, Zh$

Naturalness in Higgs to many scalars

$$L \supset H^+H \sum_{i,j}^{N} \lambda_{ij} S_i S_j + \ \dots, \qquad N \gg 1$$

$$h \to S_i S_j \to b\bar{b}, c\bar{c}, \tau\bar{\tau}$$

$$h \to S_i S_j \to \ S_i S_k S_l \to 3 \text{ times } \ b\bar{b}, c\bar{c}, \tau\bar{\tau}$$

$$h \to S_i S_j \to \ S_n S_m S_k S_l \to 4\, times \ b\bar{b}, c\bar{c}, \tau\bar{\tau}$$

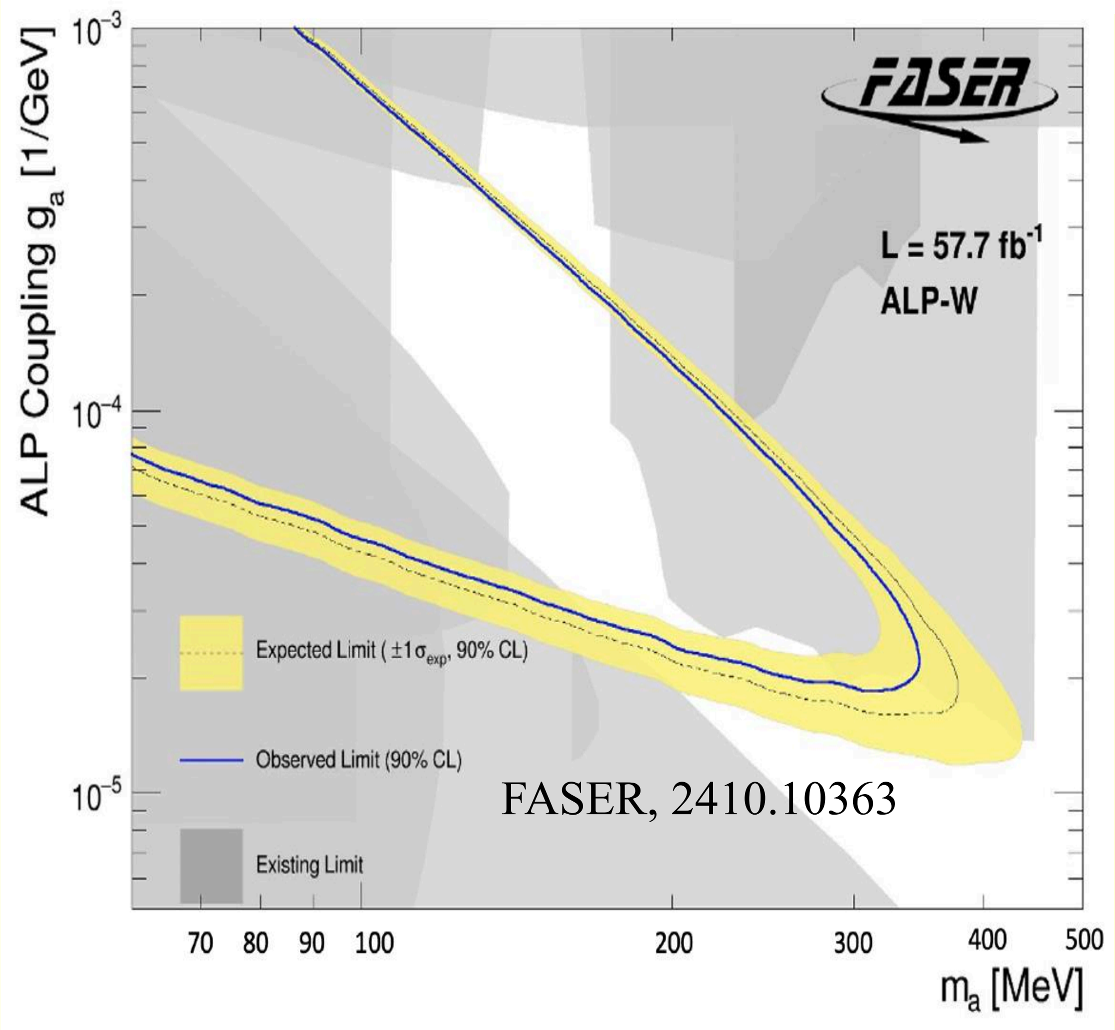
……………………

Rate into a particular final decay chain $\propto \lambda^2 \sim \frac{1}{N^2}$, **tiny**

$h \to b, c, \tau, \dots . rich\ states, however, not\ reconstructing\ particular\ resonances$

D’Agnolo, Ettenggruber

Axion-like particles



FASER, 2410.10363

Window of opportunity

LHC within striking distance

QCD axion is a primary target.

$$\boldsymbol{a\gamma\gamma}: L = \frac{-1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F^{\mu\nu}} \rightarrow \boldsymbol{g_{a\gamma\gamma}} \propto \frac{\alpha}{2\pi}\frac{1}{f_a} = \frac{\alpha}{2\pi}\frac{m_a}{\Lambda_{QCD}^2} \sim few \times 10^{-5} GeV^{-1}$$

Light scalars @ $100fb^{-1}$ +

	CMS	ATLAS
$h \to aa \to 4\tau$	$4-15\ GeV$	$4-15\ GeV$
$\to 4b$	15-60 GeV	12 – 60 GeV
$\to 4\mu$	$0.21-60\ GeV$	$1-60\ GeV$
$\to 2\mu 2b$	$15-60\ GeV$ $+2\tau 2b$	16 - 62 GeV
$h \to Za \to 2l2g$		$0.5-4\ GeV$

$\mathrm{H} \to aa \to xxxx\ (invisible)$

x′s are stable neutral particles

Theory … Lessons…

My view:

- One of the acceptable lessons is that the THs and the LHC experimentalists *are drifting apart a bit*

- Not just via papers, citations, different indices, conferences, TH & EXP seminars in JINR, RF, Europe, US, …

- THs can *change view* on EXP easily that EXP's colleagues

- THs may *switch focus* to another EXP directions, e.g. related to exotics, DM, … Cosmology,…

Formal theories since 2026- …

1. Quantum theory/gravity correspondence:
   a) Generalized to cosmological/physical spacetimes?
   b) Made precise and predictive beyond AdS/CFT?

2. Efficiently characterized space of theories (discrete or continuous)?

3. Formal methods (QFT/S-matrix) emerging as an alternative to lattice, e.g., QCD and collider physics?

4. Ideas to extract observables from QFT/Beyond QFT?

5. Quantification of degree of global symmetry breaking in quantum gravity.

What’d we do in the future …?

❑ *Standard SM extension (‘E’ frontier)*

- Push mass limits on EW particles
- Special attention to low efficiency and/or low rate signals
- Need high precision BGR

❑ *Dark/hidden SM extension (‘L’ frontier)*

- Varied, non-standard signature
- Need still more innovation in EXP
- Need (urgently) improvements in TH predictions

What'd we do in the future …?

❑ *Unexpected*

- Bizarre signals?
- TH: What principles should be tested?
- Ultra-TH: What else is inside this room?

Some form of BSM ***must exist*** anyway, to explain DM, CPV, m_ν, …

What’s important for JINR in next decade(s) with (HL)-LHC

My view

- Think of more creative ideas in case you don’t get a sci./adm. leading team chair at CERN collaborations (see, e.g., FNAL, … other non-member states at CERN)

- *Naturalness* does add the bright statement in collaboration – not be a problem for JINR. It can’t be failed.

- We are not confronting one in the sci. society, but rather adding our impact to greatest mysteries in science.

- If we don’t understand why we need it, …… *we don’t deserve it*.

An activity with sci./adm. impacts to CERN from JINR remain relevant possibilities


EXP
TH