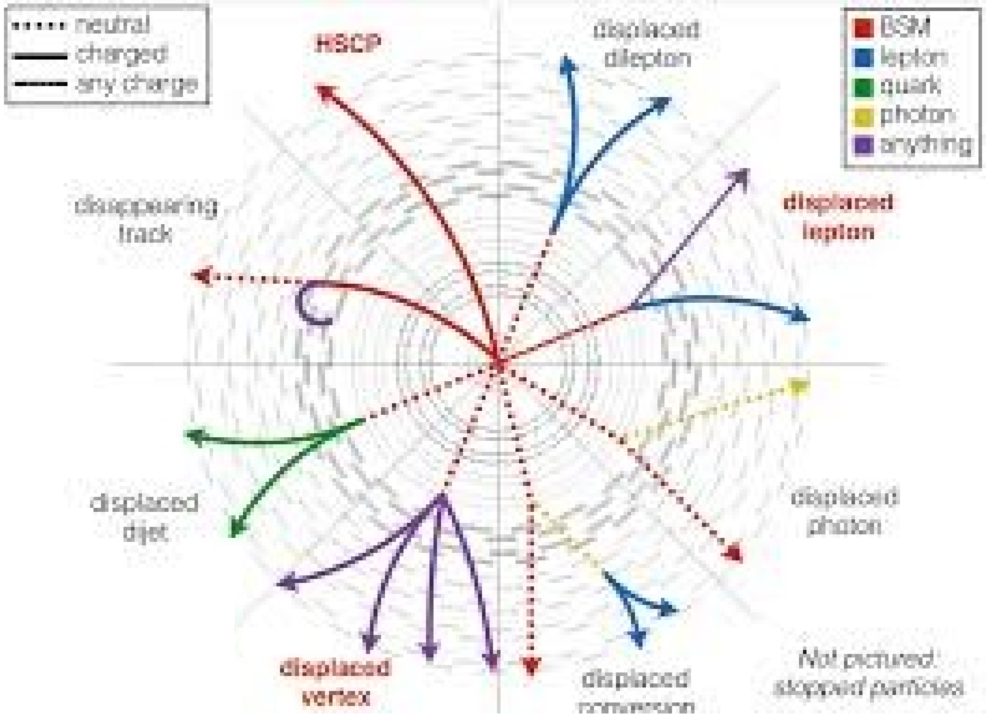
# Hidden sector and long-lived particles



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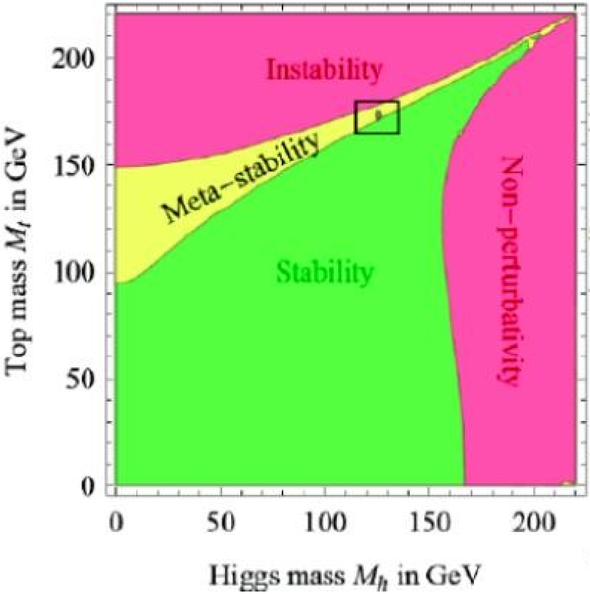
# The standard Model and beyond

- All SM particles have been discovered so far (apart from anti-ντ)
- Despite some anomalies, no compelling evidence of new physics found so far
- The Higgs mass points to a (meta-) stable universe
- The SM could be valid to the Plank scale

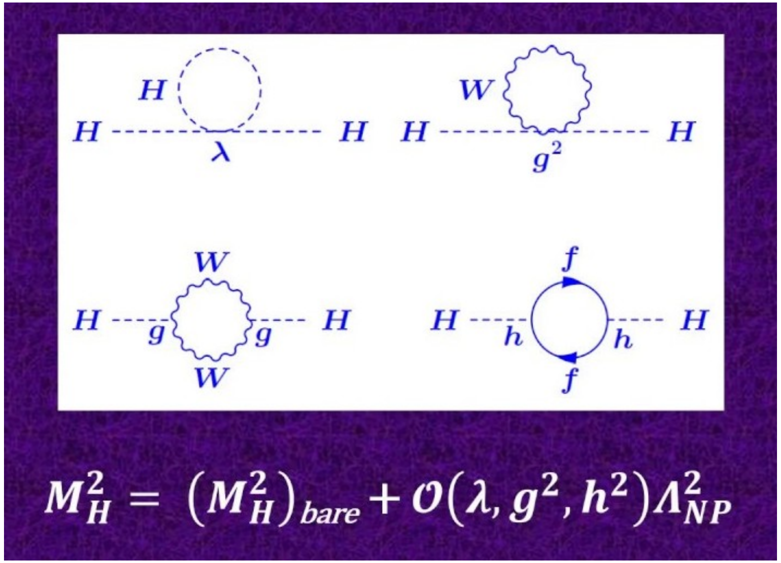


http://arxiv.org/pdf/1307.3536v2.pdf

Naturalness only a problem if we assume new particles between the EW and Plank scales

# Fine-tuning and naturaleness: the Higgs mass problem

- The Higgs mass is the sum of two terms: one bare, one from radiative corrections.
- If there is a new scale between the EW and Plank, these corrections can be very large and negative. To obtain the small mass of 125 GeV, the unknown bare mass must be very close to the corrections, and this looks very unnatural
- One of the reasons SuperSymmetry is (was?) popular is that the Higgs corrections are canceled by SUSY fermions and bosons in the loops



$$M_H^2 = (M_H^2)_{bare} + \mathcal{O}(\lambda, g^2, h^2)\Lambda_{NP}^2$$

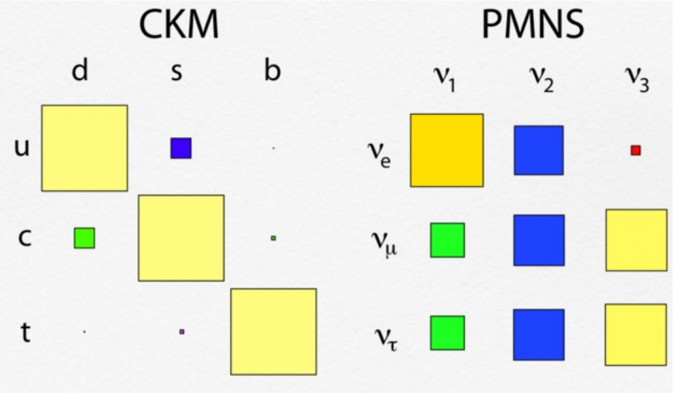
# What we know we do not know

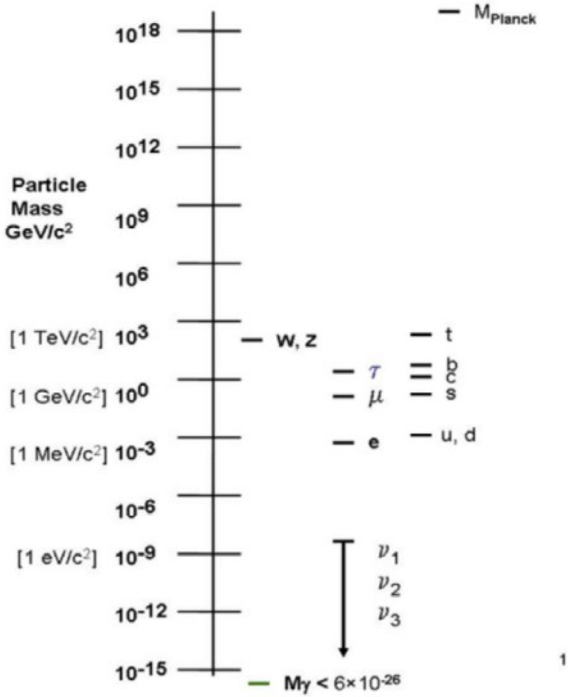
Apart from naturalness, we do not understand:

- Baryon Asymmetry of the Universe
  - Why we have much more matter than antimatter
  - Need CP violation, but the one found in quarks is not sufficient, need mechanism for leptogenesys
- Dark Matter (indications are for cold, non-baryonic)
  - Many astrophysical indicators point to missing invisible mass in galaxies. Cannot be too light, otherwise structure formation would be different

# What we know we do not know (2)

- The pattern of masses and mixings

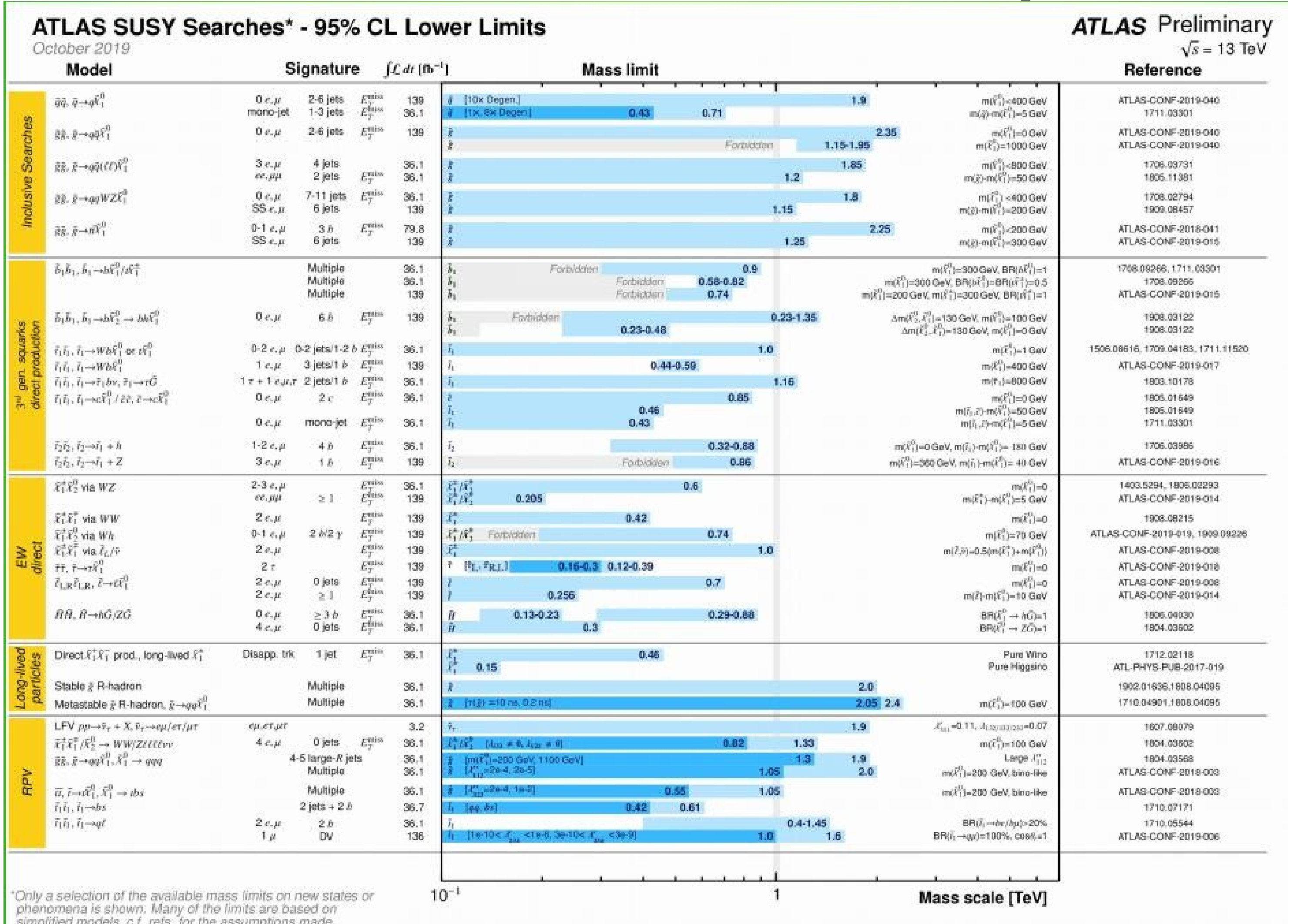




- Inflation
  - What happened just after the big bang?
- Limits to masses of new particles being pushed in the TeV scale by the LHC.

→ “protection” against a small Higgs mass getting weaker

# Mass limits for SUSY particles



**ATLAS SUSY Searches* - 95% CL Lower Limits**

October 2019

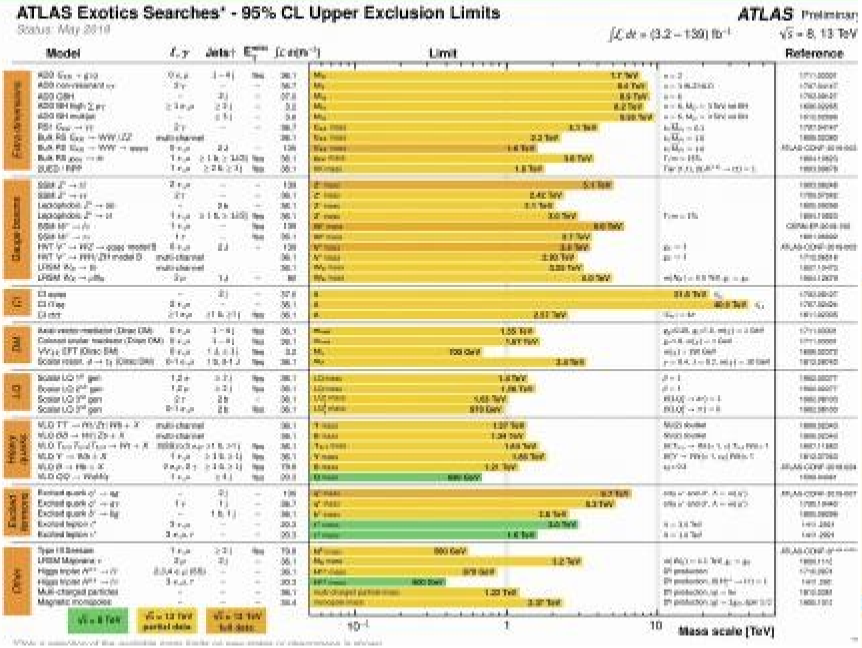
***ATLAS*** Preliminary

$\sqrt{s}$ = 13 TeV

| | Model | Signature | | | $\int \mathcal{L}\,dt$ [fb$^{-1}$] | Mass limit | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ | 0 $e,\mu$ | 2-6 jets | $E_T^{\rm miss}$ | 139 | $\tilde{q}$ [10x Degen.] | 1.9 | m($\tilde{\chi}^0_1$)<400 GeV | ATLAS-CONF-2019-040 |
| | | mono-jet | 1-3 jets | $E_T^{\rm miss}$ | 36.1 | $\tilde{q}$ [1x, 8x Degen.] | 0.43 0.71 | m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$ | 0 $e,\mu$ | 2-6 jets | $E_T^{\rm miss}$ | 139 | $\tilde{g}$ | 2.35 | m($\tilde{\chi}^0_1$)=0 GeV | ATLAS-CONF-2019-040 |
| | | | | | | $\tilde{g}$ Forbidden | 1.15-1.95 | m($\tilde{\chi}^0_1$)=1000 GeV | ATLAS-CONF-2019-040 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$ | 3 $e,\mu$ | 4 jets | | 36.1 | $\tilde{g}$ | 1.85 | m($\tilde{\chi}^0_1$)<800 GeV | 1706.03731 |
| | | $ee,\mu\mu$ | 2 jets | $E_T^{\rm miss}$ | 36.1 | $\tilde{g}$ | 1.2 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.11381 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$ | 0 $e,\mu$ | 7-11 jets | $E_T^{\rm miss}$ | 36.1 | $\tilde{g}$ | 1.8 | m($\tilde{\chi}^0_1$) <400 GeV | 1708.02794 |
| | | SS $e,\mu$ | 6 jets | | 139 | $\tilde{g}$ | 1.15 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV | 1909.08457 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$ | 0-1 $e,\mu$ | 3 $b$ | $E_T^{\rm miss}$ | 79.8 | $\tilde{g}$ | 2.25 | m($\tilde{\chi}^0_1$)<200 GeV | ATLAS-CONF-2018-041 |
| | | SS $e,\mu$ | 6 jets | | 139 | $\tilde{g}$ | 1.25 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV | ATLAS-CONF-2019-015 |
| 3rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^{\pm}_1$ | | Multiple | | 36.1 | $\tilde{b}_1$ Forbidden | 0.9 | m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1 | 1708.09266, 1711.03301 |
| | | | Multiple | | 36.1 | $\tilde{b}_1$ Forbidden | 0.58-0.82 | m($\tilde{\chi}^0_1$)=300 GeV, BR($t\tilde{\chi}^{\pm}_1$)=BR($b\tilde{\chi}^0_1$)=0.5 | 1708.09266 |
| | | | Multiple | | 139 | $\tilde{b}_1$ Forbidden | 0.74 | m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^{\pm}_1$)=300 GeV, BR($t\tilde{\chi}^{\pm}_1$)=1 | ATLAS-CONF-2019-015 |
| | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$ | 0 $e,\mu$ | 6 $b$ | $E_T^{\rm miss}$ | 139 | $\tilde{b}_1$ Forbidden | 0.23-1.35 | $\Delta$m($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV | 1908.03122 |
| | | | | | | $\tilde{b}_1$ | 0.23-0.48 | $\Delta$m($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV | 1908.03122 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | $E_T^{\rm miss}$ | 36.1 | $\tilde{t}_1$ | 1.0 | m($\tilde{\chi}^0_1$)=1 GeV | 1506.08616, 1709.04183, 1711.11520 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ | 1 $e,\mu$ | 3 jets/1 $b$ | $E_T^{\rm miss}$ | 139 | $\tilde{t}_1$ | 0.44-0.59 | m($\tilde{\chi}^0_1$)=400 GeV | ATLAS-CONF-2019-017 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$ | $1\tau+1\,e,\mu,\tau$ | 2 jets/1 $b$ | $E_T^{\rm miss}$ | 36.1 | $\tilde{t}_1$ | 1.16 | m($\tilde{\tau}_1$)=800 GeV | 1803.10178 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$ | 0 $e,\mu$ | 2 $c$ | $E_T^{\rm miss}$ | 36.1 | $\tilde{c}$ | 0.85 | m($\tilde{\chi}^0_1$)=0 GeV | 1805.01649 |
| | | | | | | $\tilde{t}_1$ | 0.46 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.01649 |
| | | 0 $e,\mu$ | mono-jet | $E_T^{\rm miss}$ | 36.1 | $\tilde{t}_1$ | 0.43 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$ | 1-2 $e,\mu$ | 4 $b$ | $E_T^{\rm miss}$ | 36.1 | $\tilde{t}_2$ | 0.32-0.88 | m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV | 1706.03986 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$ | 3 $e,\mu$ | 1 $b$ | $E_T^{\rm miss}$ | 139 | $\tilde{t}_2$ Forbidden | 0.86 | m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV | ATLAS-CONF-2019-016 |
| EW direct | $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via $WZ$ | 2-3 $e,\mu$ | | $E_T^{\rm miss}$ | 36.1 | $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ | 0.6 | m($\tilde{\chi}^0_1$)=0 | 1403.5294, 1806.02293 |
| | | $ee,\mu\mu$ | $\geq 1$ | $E_T^{\rm miss}$ | 139 | $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ | 0.205 | m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=5 GeV | ATLAS-CONF-2019-014 |
| | $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via $WW$ | 2 $e,\mu$ | | $E_T^{\rm miss}$ | 139 | $\tilde{\chi}^{\pm}_1$ | 0.42 | m($\tilde{\chi}^0_1$)=0 | 1908.08215 |
| | $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via $Wh$ | 0-1 $e,\mu$ | 2 $b$/2 $\gamma$ | $E_T^{\rm miss}$ | 139 | $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ Forbidden | 0.74 | m($\tilde{\chi}^0_1$)=70 GeV | ATLAS-CONF-2019-019, 1909.09226 |
| | $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 $e,\mu$ | | $E_T^{\rm miss}$ | 139 | $\tilde{\chi}^{\pm}_1$ | 1.0 | m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$)) | ATLAS-CONF-2019-008 |
| | $\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$ | 2 $\tau$ | | $E_T^{\rm miss}$ | 139 | $\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] | 0.16-0.3 0.12-0.39 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-018 |
| | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$ | 2 $e,\mu$ | 0 jets | $E_T^{\rm miss}$ | 139 | $\tilde{\ell}$ | 0.7 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-008 |
| | | 2 $e,\mu$ | $\geq 1$ | $E_T^{\rm miss}$ | 139 | $\tilde{\ell}$ | 0.256 | m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV | ATLAS-CONF-2019-014 |
| | $\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 $e,\mu$ | $\geq 3\,b$ | $E_T^{\rm miss}$ | 36.1 | $\tilde{H}$ | 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1 | 1806.04030 |
| | | 4 $e,\mu$ | 0 jets | $E_T^{\rm miss}$ | 36.1 | $\tilde{H}$ | 0.3 | BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1 | 1804.03602 |
| Long-lived particles | Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$ | Disapp. trk | 1 jet | $E_T^{\rm miss}$ | 36.1 | $\tilde{\chi}^{\pm}_1$ | 0.46 | Pure Wino | 1712.02118 |
| | | | | | | $\tilde{\chi}^{\pm}_1$ | 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019 |
| | Stable $\tilde{g}$ R-hadron | | Multiple | | 36.1 | $\tilde{g}$ | 2.0 | | 1902.01636,1808.04095 |
| | Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$ | | Multiple | | 36.1 | $\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] | 2.05 2.4 | m($\tilde{\chi}^0_1$)=100 GeV | 1710.04901,1808.04095 |
| RPV | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | | | 3.2 | $\tilde{\nu}_\tau$ | 1.9 | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 $e,\mu$ | 0 jets | $E_T^{\rm miss}$ | 36.1 | $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] | 0.82 1.33 | m($\tilde{\chi}^0_1$)=100 GeV | 1804.03602 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$ | | 4-5 large-$R$ jets | | 36.1 | $\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] | 1.3 1.9 | Large $\lambda''_{112}$ | 1804.03568 |
| | | | Multiple | | 36.1 | $\tilde{g}$ [$\lambda''_{112}$=2e-4, 2e-5] | 1.05 2.0 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$ | | Multiple | | 36.1 | $\tilde{g}$ [$\lambda''_{323}$=2e-4, 1e-2] | 0.55 1.05 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | | 2 jets + 2 $b$ | | 36.7 | $\tilde{t}_1$ [$qq$, $bs$] | 0.42 0.61 | | 1710.07171 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$ | 2 $e,\mu$ | 2 $b$ | | 36.1 | $\tilde{t}_1$ | 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544 |
| | | 1 $\mu$ | DV | | 136 | $\tilde{t}_1$ [1e-10< $\lambda'_{23k}$ <1e-8, 3e-10< $\lambda'_{23k}$ <3e-9] | 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, cos$\theta_t$=1 | ATLAS-CONF-2019-006 |

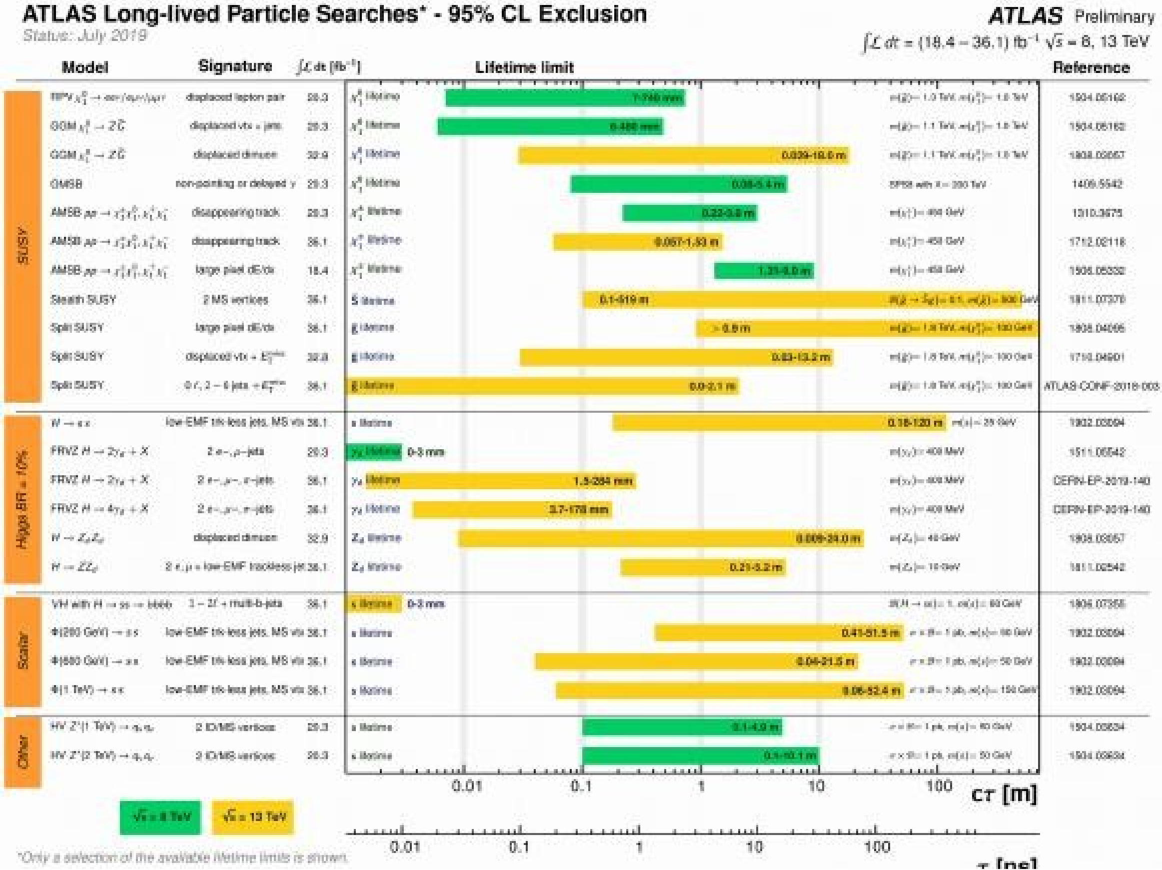
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# Limits on “exotic” particles



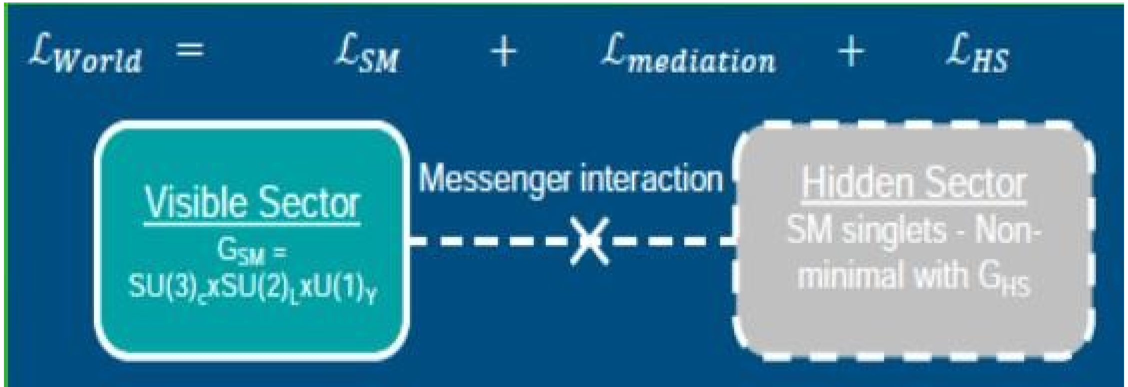
← mass limits

Limits on lifetimes of long-lived particles (in ATLAS, limited by detector size)



# The “hidden sector” approach to new physics

- Maybe new particles have not been found yet not because they are heavy, but because their coupling is very small, or null
- If an additional term to the Lagrangian is not interacting with SM, there could be invisible particles contributing to dark matter, and no naturalness issues
- However, an interference term between the Lagrangians would allow a very small coupling:



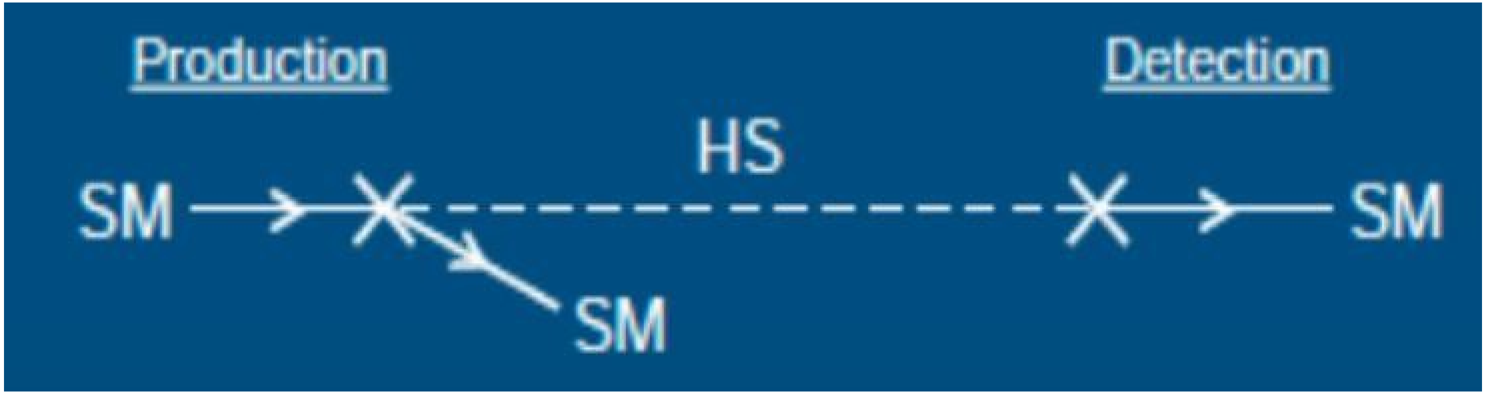
$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{O_{HS}^{(k)} O_{SM}^{(l)}}{\Lambda^n}$$

# How to detect a hidden particle?

Indications for a Hidden Sector may come from “ordinary” particles (SM, SUSY, axions etc.) acting as mediators with the HS Lagrangian

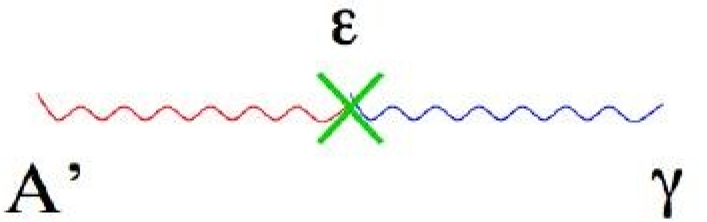
- The experimental signature is either missing energy or the appearance of SM particles very far away from its production, indicating an “oscillation” into the HS (and back)



# Examples of Portals

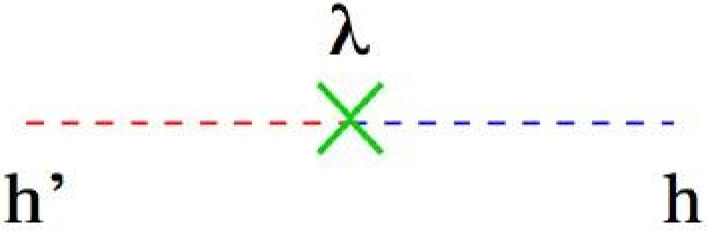
- Vector Portal:
  (A' = "hidden photon" )

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$



- Higgs Portal:
  (H' = "hidden Higgs")

$$\lambda |H'|^2 |H|^2$$



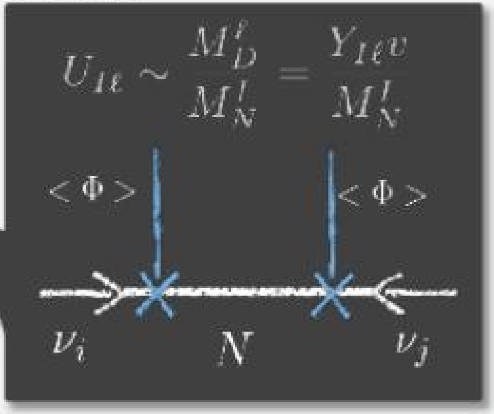
# Sterile neutrinos

Fermions get mass via the Yukawa couplings:

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi} U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.}$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic Lagrangian is

$$\underbrace{\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i}_{\text{Kinetic term}} - \underbrace{\frac{1}{2}M_{ij}\overline{N^c}_i N_j}_{\text{Majorana mass term}} - \underbrace{Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j}_{\text{Yukawa coupling}}$$



$$U_{I\ell} \sim \frac{M^\ell_D}{M^I_N} = \frac{Y_{I\ell}v}{M^I_N}$$

Seesaw mechanism:

$$\mathcal{V} = (\nu_{Li}, N_j)$$

$$-\mathcal{L}_{M_\mathcal{V}} = \frac{1}{2}\overline{\mathcal{V}}M_\mathcal{V}\mathcal{V} + h.c.$$

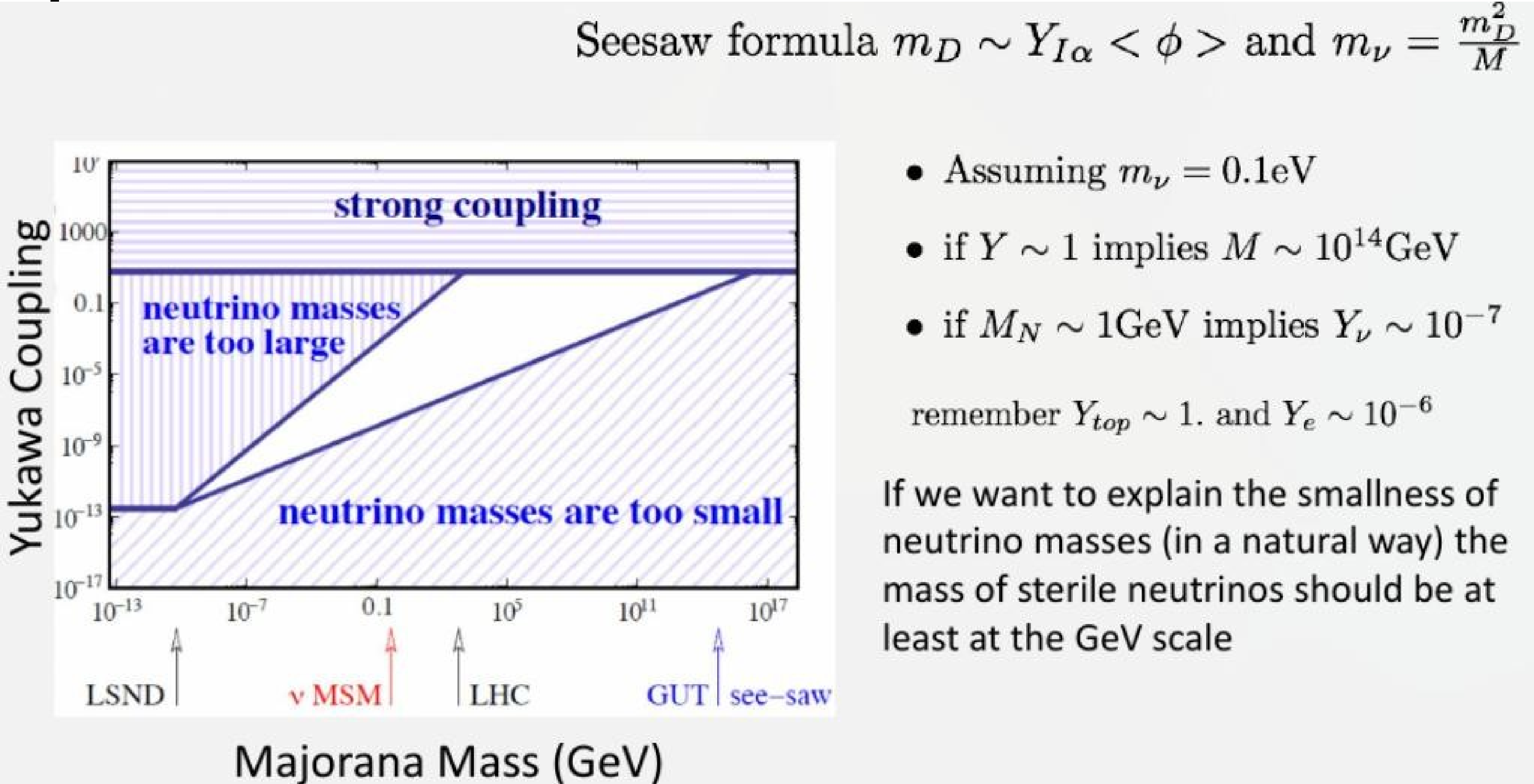
if $M_N \gg M_D$:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ {M_D}^T & M_N \end{pmatrix} \quad \lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

# The see-saw mechanism: a possible explanation of small neutrino masses



Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$

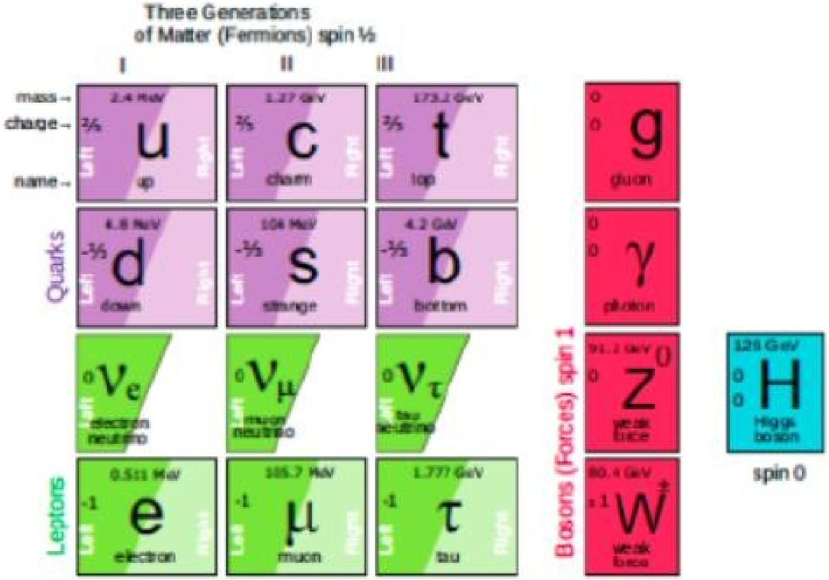
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

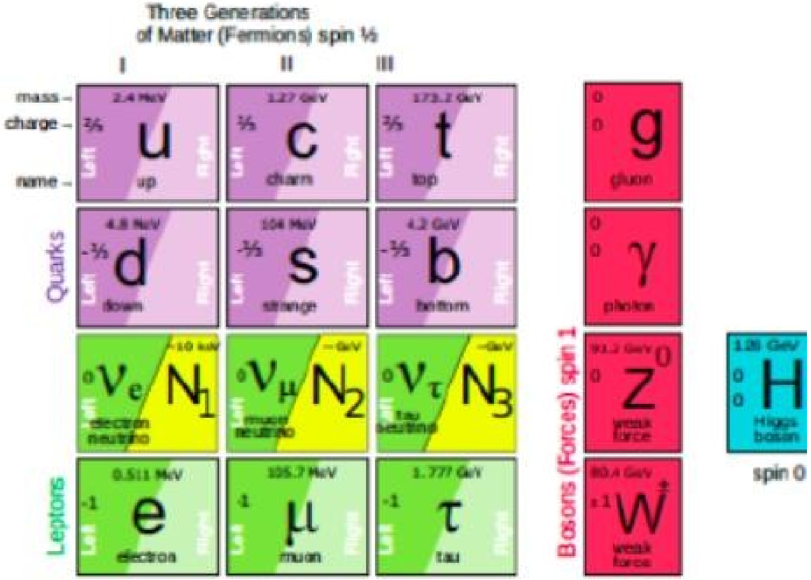
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

# The νMSSM

T.Asaka, M.Shaposhnikov PL B620 (2005) 17
M.Shaposhnikov, Nucl. Phys. B763 (2007) 49



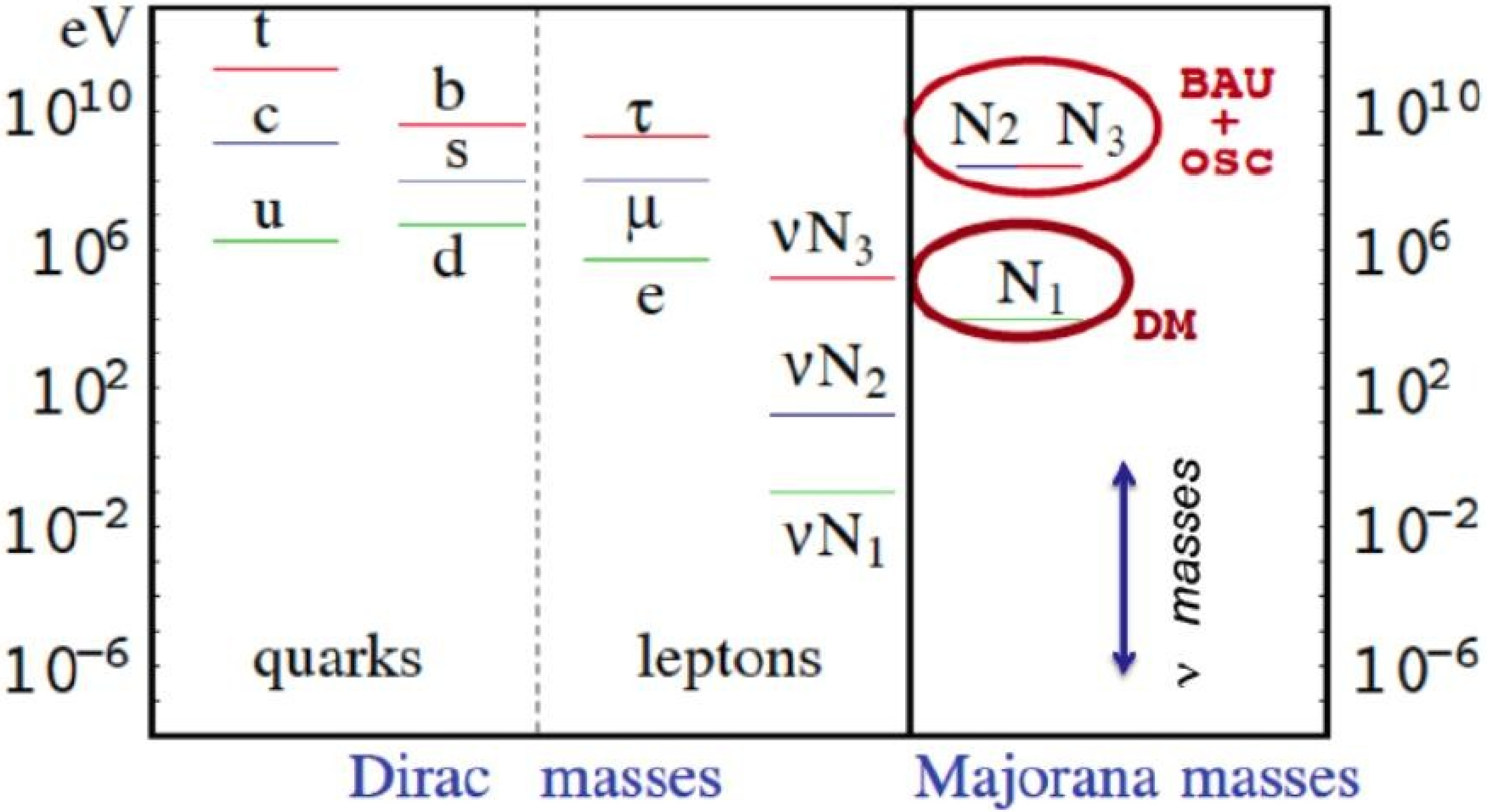


Particle content of SM made symmetric by adding 3 HNL: N1, N2 , N3

With M(N ) ~ few KeV, it is a good DM candidate (or DM can be generated outside ofthis model through decay of inflaton)

With M(N , N ) ~ GeV, could explain Barion Asymmetry of Universe (via leptogenesis),and generate neutrino masses through see-saw.

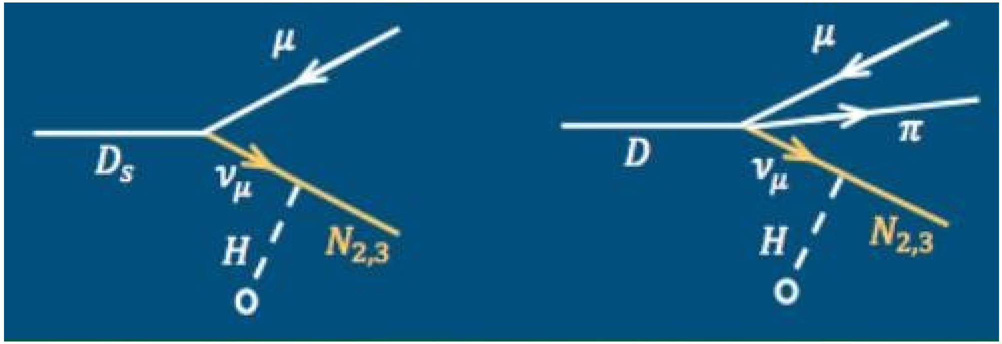
# Mass ranges for sterile neutrinos

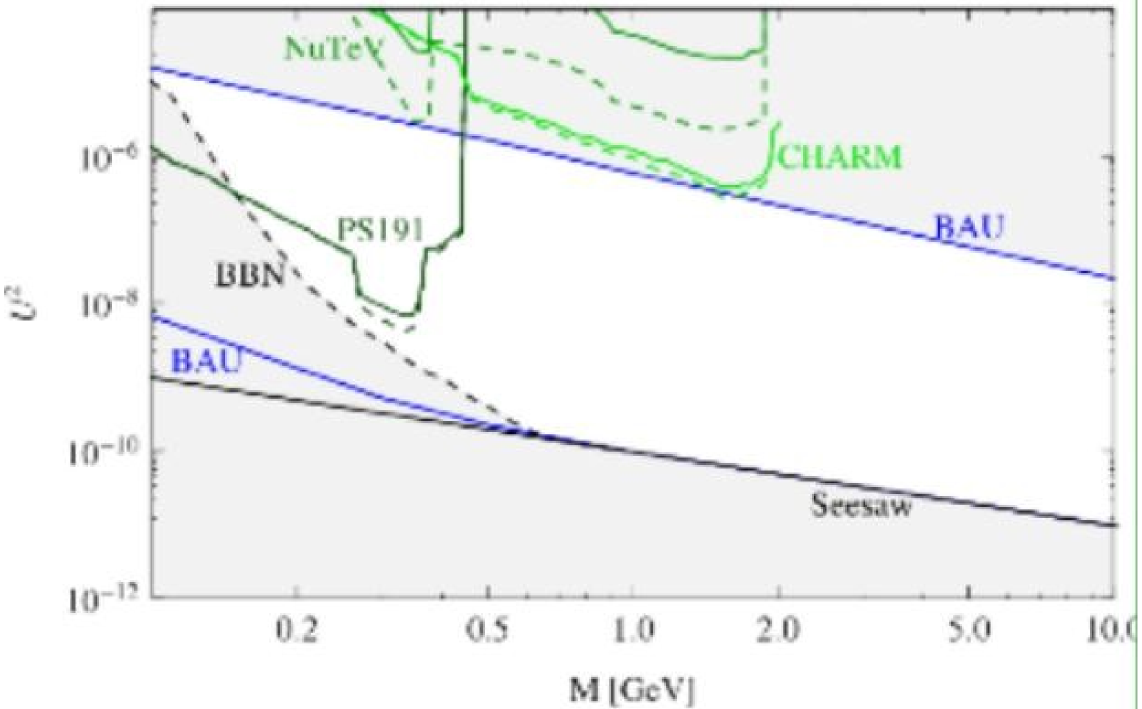


# HNL production mechanism

Interaction with Higgs vev leads to a mixing with active neutrinos
Several past searches; PS191 used neutrinos from K decays, while other experiments not sensitive to mixings of cosmological interest.

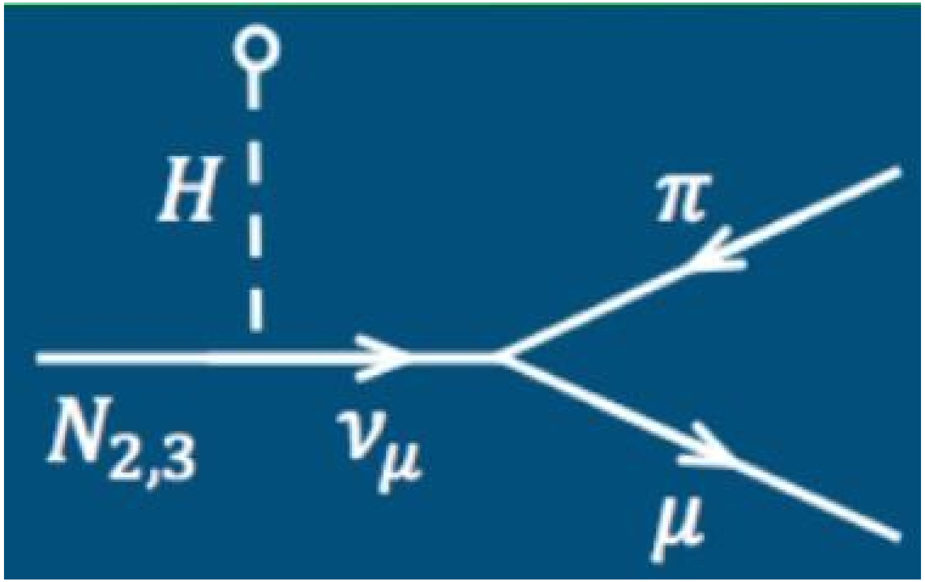
Latest result: LHCb with B decays obtained U2≈10-4, arXiv:1401.5361
Further exploration needed of the region with higher masses and smaller mixings

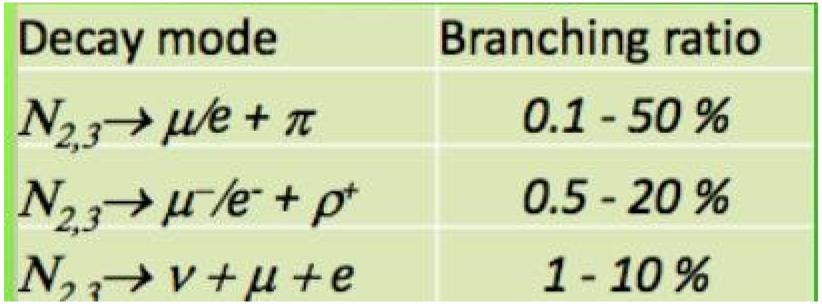




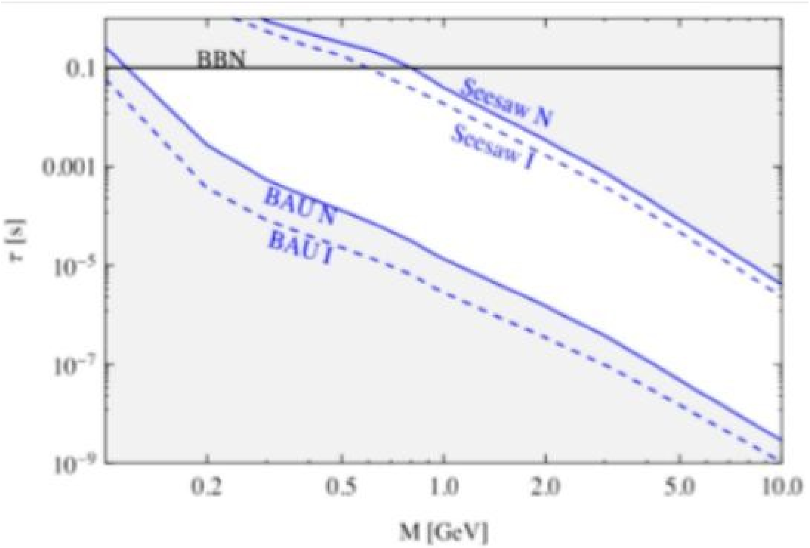
# HNL decays

- Interaction with Higgs vev would make it
- oscillate back into a virtual neutrino, that
- produces a muon and a W (→ hadrons, eg pions)
- Exact branching fractions depend n flavor mixing
- Due to small couplings, ms lifetimes, decay paths O(km)



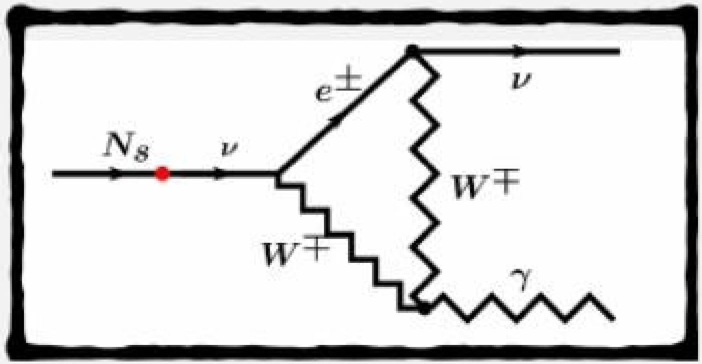


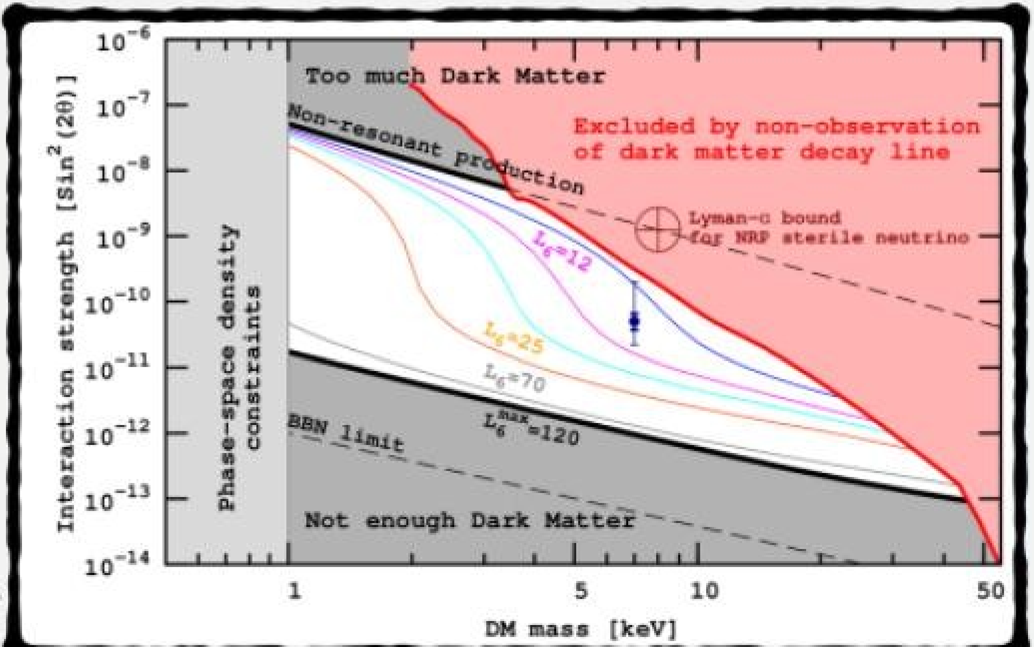
| Decay mode | Branching ratio |
|---|---|
| $N_{2,3} \rightarrow \mu/e + \pi$ | 0.1 - 50 % |
| $N_{2,3} \rightarrow \mu^-/e^- + \rho^+$ | 0.5 - 20 % |
| $N_{2,3} \rightarrow \nu + \mu + e$ | 1 - 10 % |



# Constraints on N1 mass

DM sterile neutrinos decay subdominantly as $N_1 \to \nu\gamma$ with a branching ration $\mathcal{B}(N_1 \to \gamma\nu) \sim \frac{1}{123}$



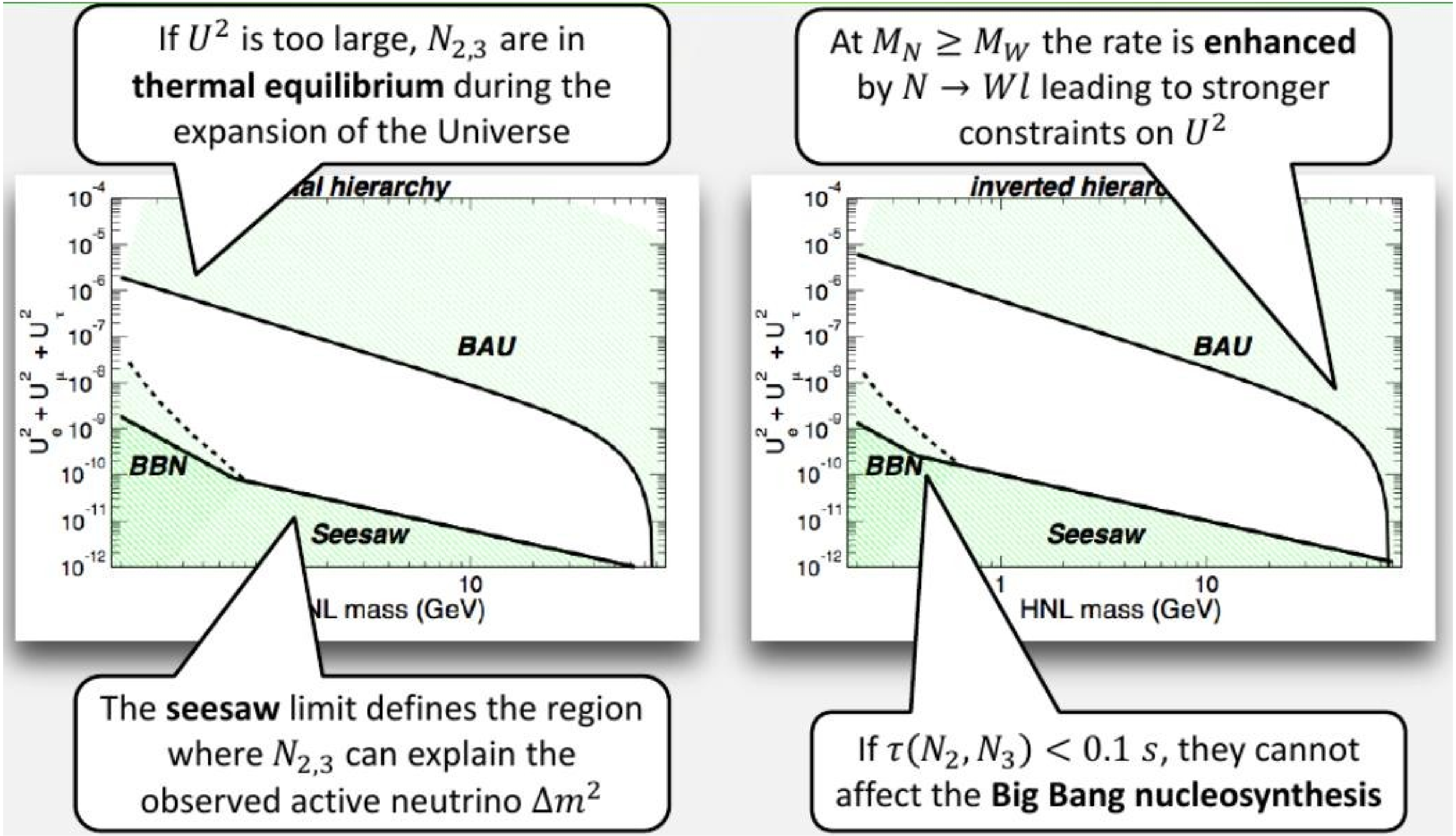


Discussion in the community, not yet clear if this is a “good” signal, needs confirmation

Bulbul et al. 2014 (arXiv:1402.2301)

Boyarsky et al. 2014 (arXiv:1402.4119)

# Constraints on N2, N3 masses



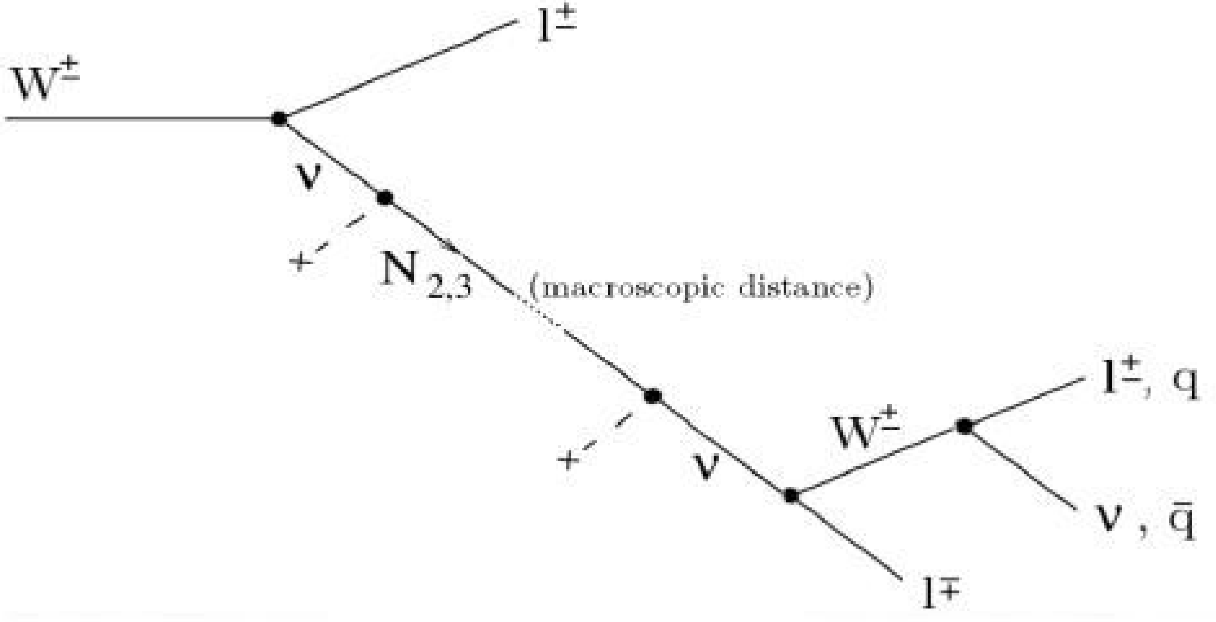
If $U^2$ is too large, $N_{2,3}$ are in **thermal equilibrium** during the expansion of the Universe

At $M_N \geq M_W$ the rate is **enhanced** by $N \rightarrow Wl$ leading to stronger constraints on $U^2$

The **seesaw** limit defines the region where $N_{2,3}$ can explain the observed active neutrino $\Delta m^2$

If $\tau(N_2, N_3) < 0.1\ s$, they cannot affect the **Big Bang nucleosynthesis**

# High-mass searches in ATLAS: JHEP 10 (2019) 265

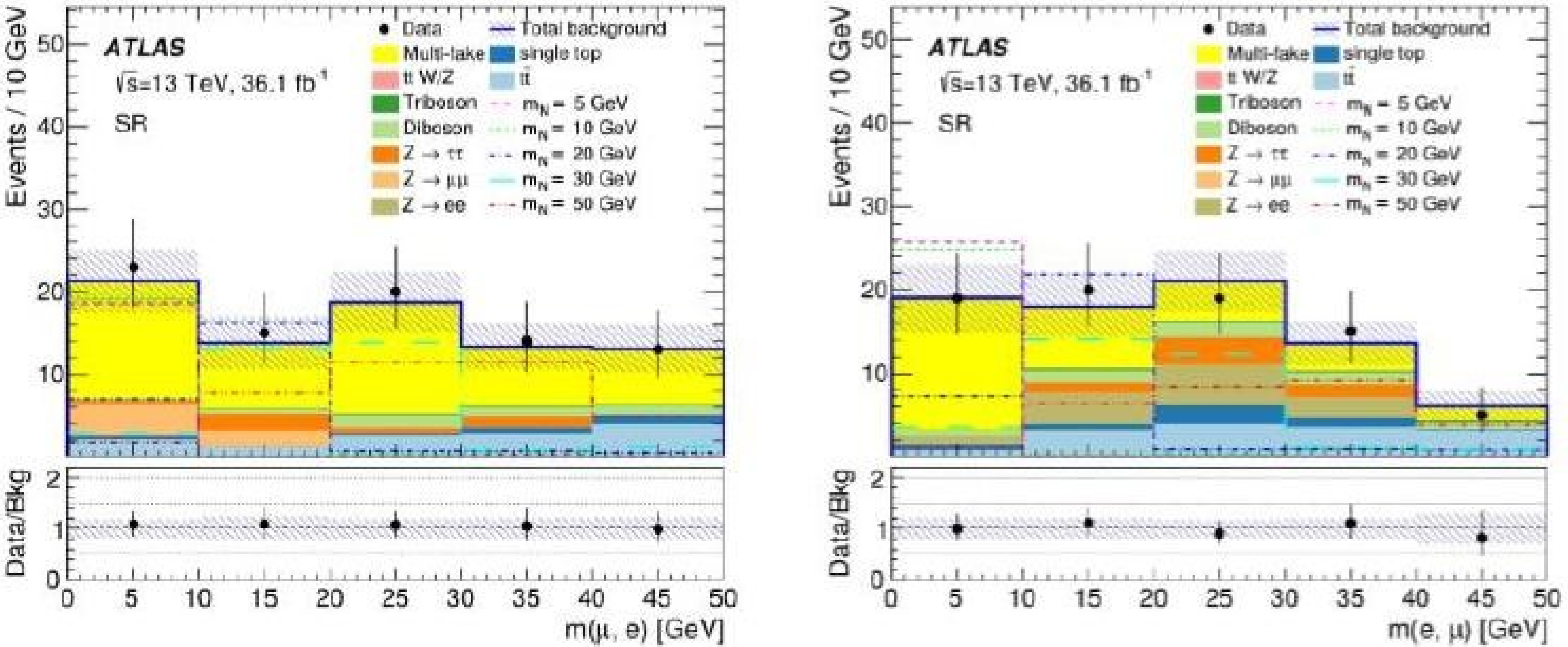


**Two signatures probed:**

1. Prompt-trilepton decay:
    - $W_\pm \rightarrow \mu_\pm \mu_\pm e_\mp \nu_e$ (mu channel)
    - $W_\pm \rightarrow e_\pm e_\pm \mu_\mp \nu_\mu$ (e channel)
2. Displaced vertex signature:
    - $W_\pm \rightarrow \mu_\pm \rightarrow \mathrm{DV} \rightarrow \mu_\pm e_\mp \nu_e$ (mu channel)

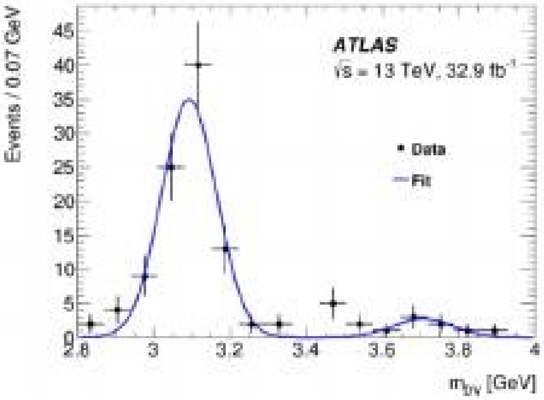
$$\sigma(pp \to W) \cdot \mathcal{B}(W \to \ell N) = \sigma(pp \to W) \cdot \mathcal{B}(W \to \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right)$$

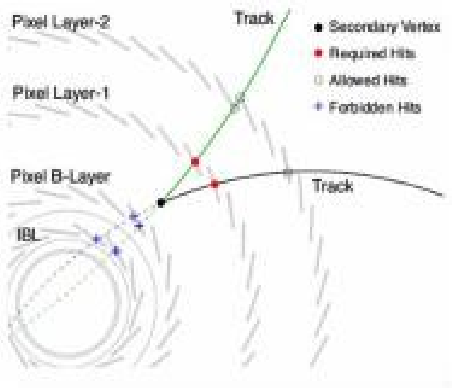
# Backgrounds: prompt-trilepton decay:

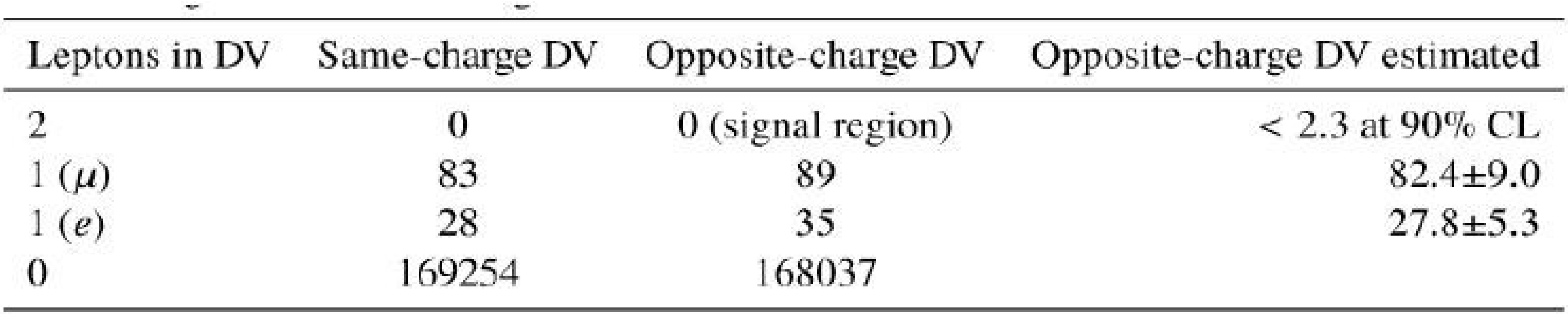


# Backgrounds: Displaced-vertex signature:

- SM background
- Cosmic Muon
- Instrumental backgrounds
- Track Accidental Crossing

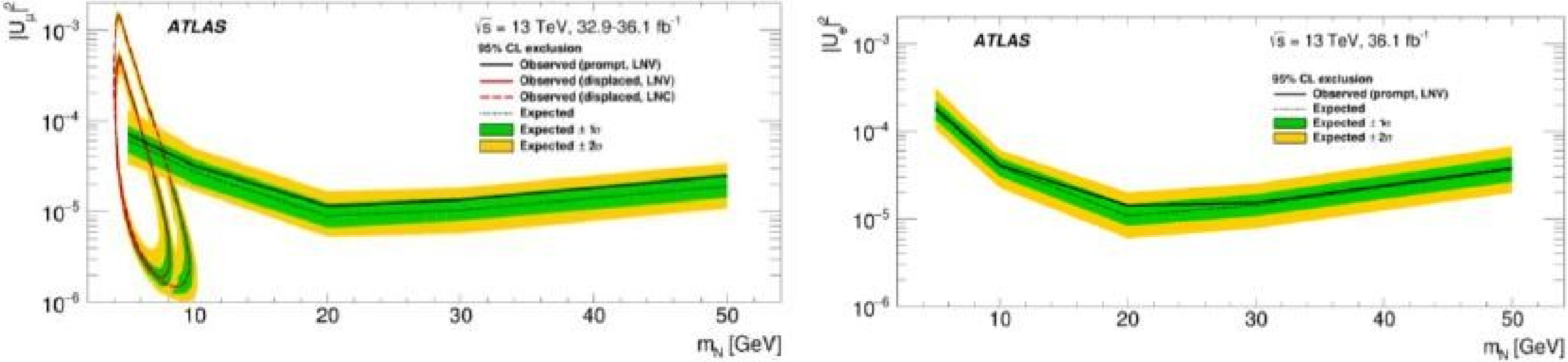






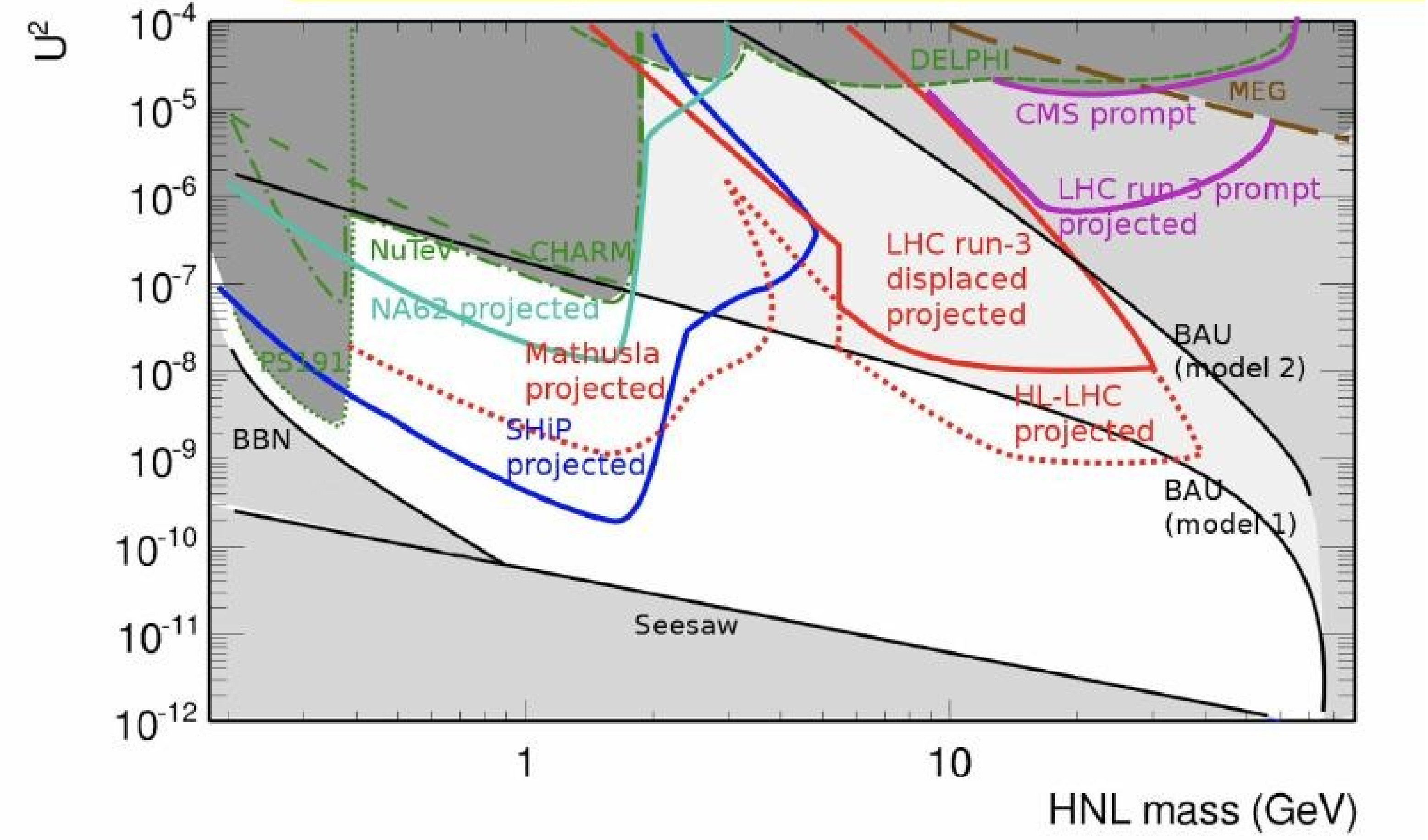
| Leptons in DV | Same-charge DV | Opposite-charge DV | Opposite-charge DV estimated |
|---|---|---|---|
| 2 | 0 | 0 (signal region) | < 2.3 at 90% CL |
| 1 ($\mu$) | 83 | 89 | 82.4±9.0 |
| 1 ($e$) | 28 | 35 | 27.8±5.3 |
| 0 | 169254 | 168037 | |

# Results:



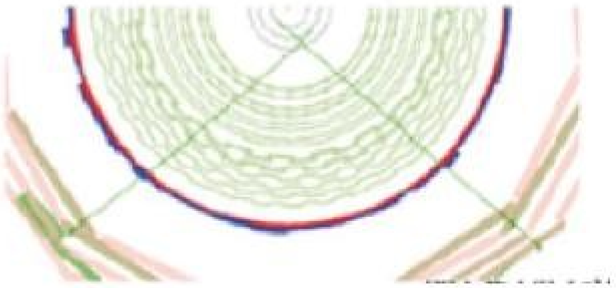
Observed 95% confidence-level exclusion in $|U_\mu|^2$ (left) and $|U_e|^2$ (right) versus the HNL mass fort he prompt signature (the region above the black line is excluded) and the displaced signature (the region enclosed by the red line is excluded). The solid lines show limits assuming lepton-number violation (LNV)for 50% of the decays and the long-dashed line shows the limit in the case of lepton-number conservation (LNC). The dotted lines show expected limits and the bands indicate the ranges of expected limits obtained within 1σ and2σ of the median limit, reflecting uncertainties in signal and background yields.

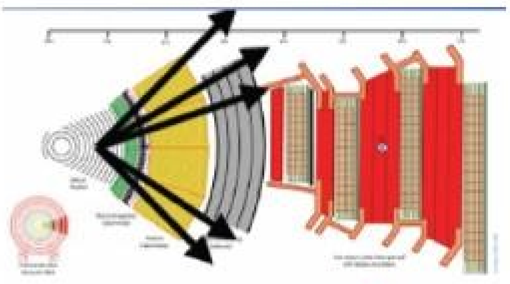
# Sensitivity prospects in the cosmologically-interesting region

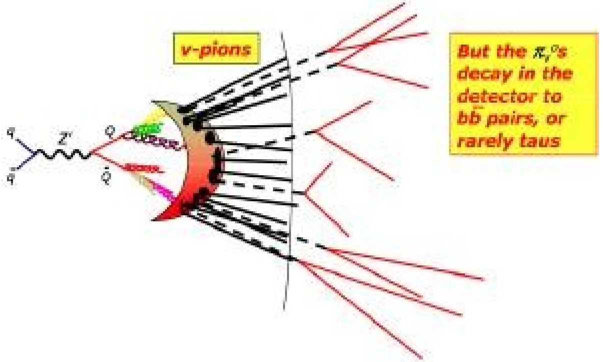


# Other searches with ATLAS/CMS

- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced leptons & lepton jets
- Displaced photons
- Dark photon decays
- Heavy Stable Charged Particles
- Stopped particles
- Emerging jets
- Monopoles stuck in material
- Heavy Neutral Lepton searches
- Strongly Interaction Massive Particles
- …. (others…new ideas… )





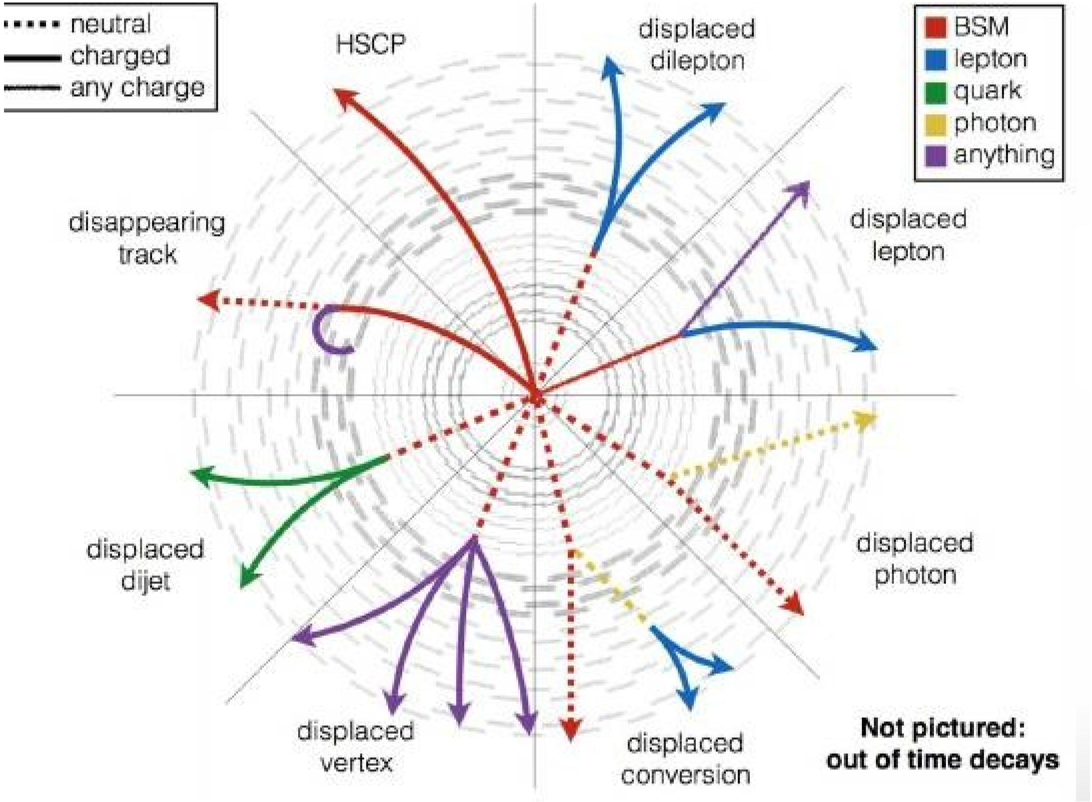


# Long-lived particles not only from hidden sector

- Many BSM theories predict existence of feebly interacting (so, long-lived) particles, often with similar signatures

- Examples:
    - SuperSymmetry (RP-Violating, SMB, Gauge-mediated, split)
    - Generic dark-matter models
    - Quirks
    - Stable Sexaquarks
    - Etc...

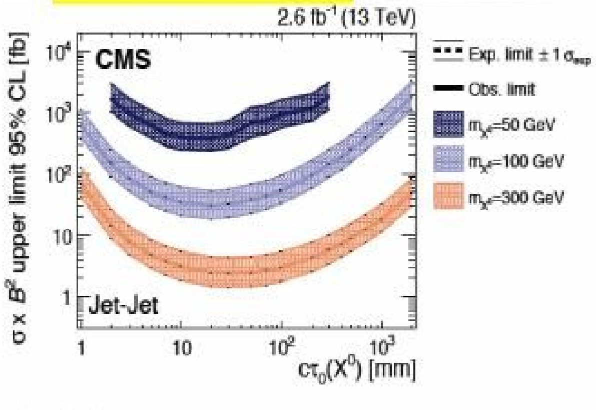
# Experimental signatures



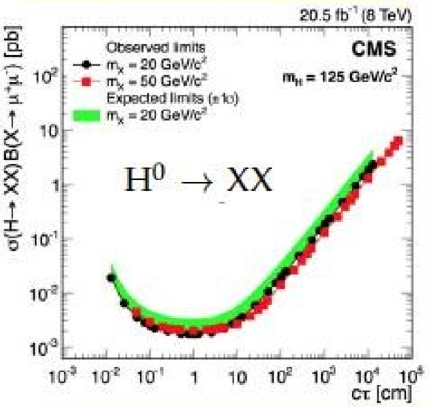
- The LHC detectors were not built for this!
- These very unusual signatures present challenges in:
  - triggering
  - tracking
  - calorimeter calibration
  - data-driven background determination
  - Etc….

# Limits on various models

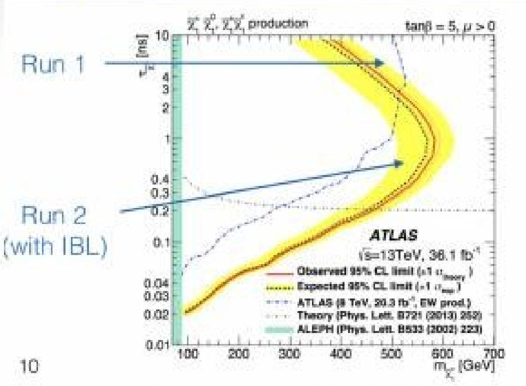
displaced jets



displaced leptons

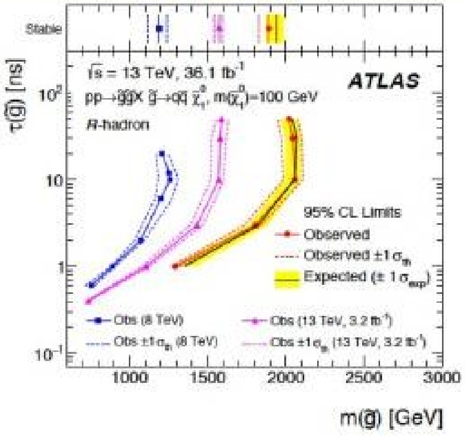


disappearing tracks

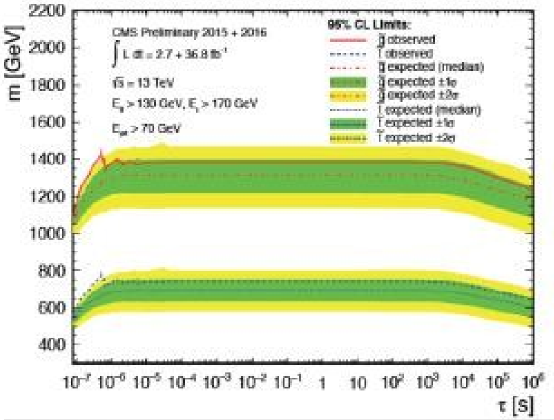

Run 1

Run 2
(with IBL)

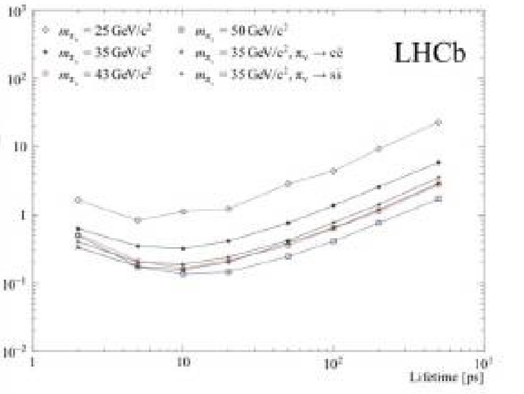
metastable R-hadrons



stopped particles

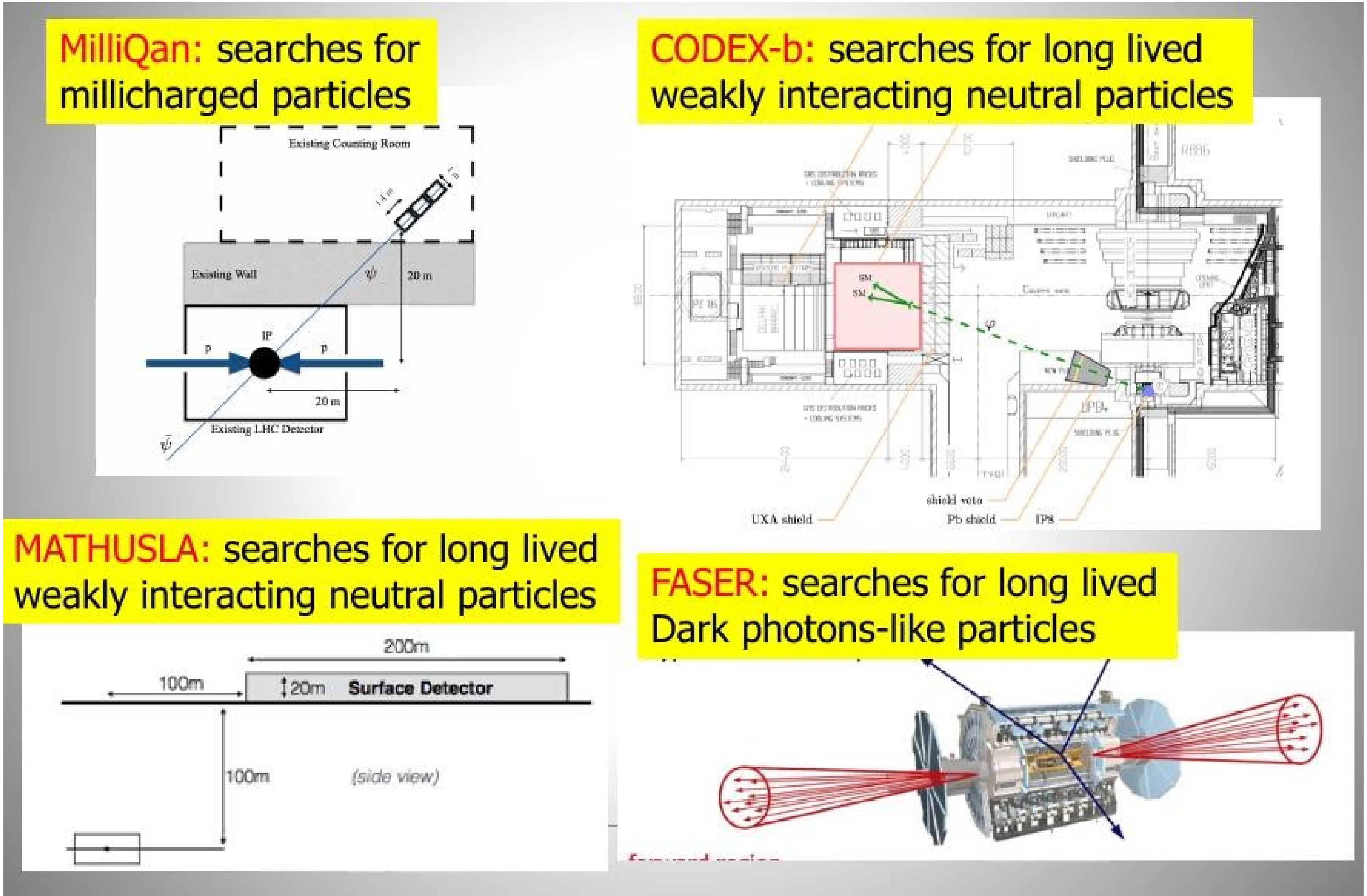


Hidden Valley searches



# Proposals for new experiments at LHC

Slides from
A.DeRoeck



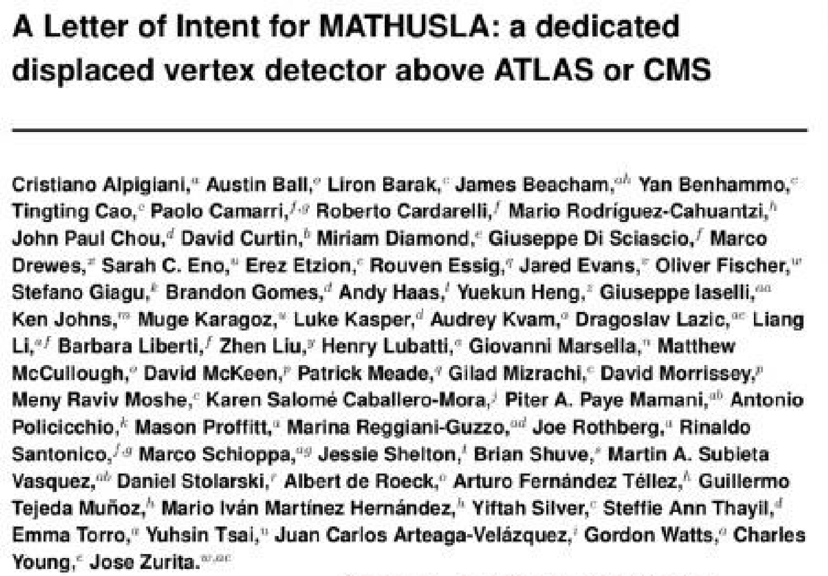
**MilliQan:** searches for millicharged particles

**CODEX-b:** searches for long lived weakly interacting neutral particles

**MATHUSLA:** searches for long lived weakly interacting neutral particles

**FASER:** searches for long lived Dark photons-like particles

# MATHUSLA



**A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS**

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Cristiano Alpigiani,[a] Austin Ball,[e] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[r] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ac] Liang Li,[a,f] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[c] Jose Zurita.[w,ae]

CERN-LHCC-2018-25

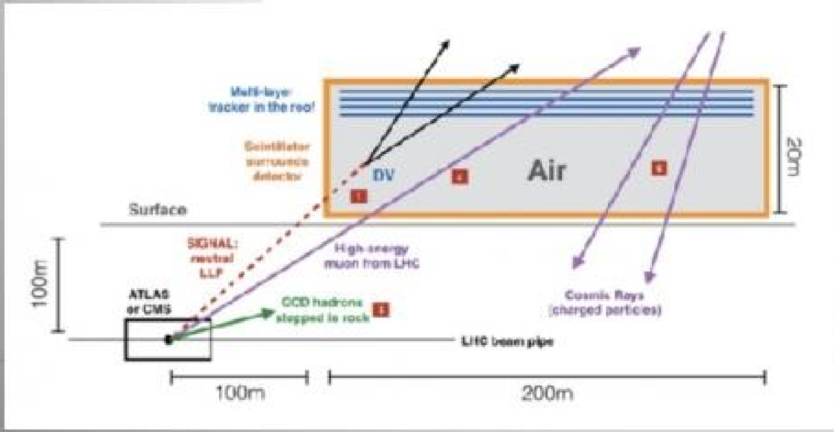
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

Aim to cover the range

$$c\tau \lesssim 10^7 - 10^8\ \mathrm{m}$$

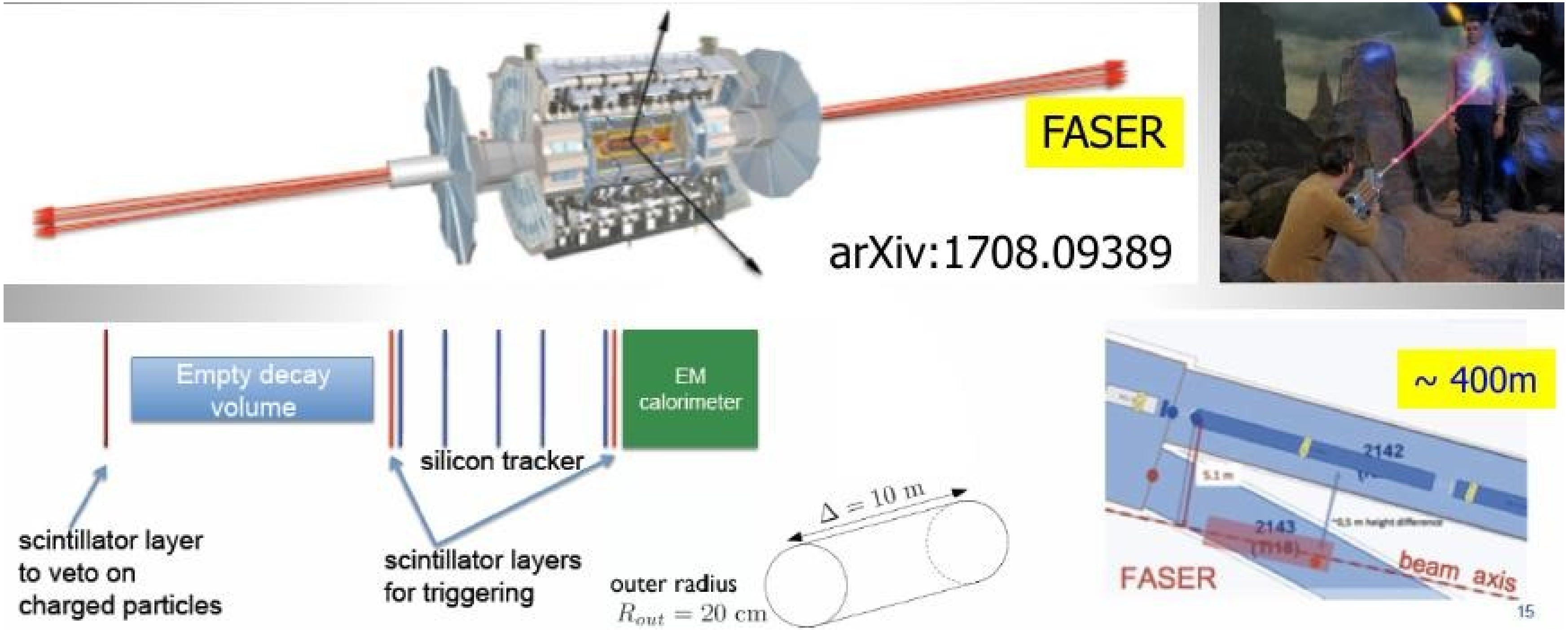
~ BBN constrained inspired

Physic case arXiv:1806.07396



Possible detector surface array eg above ATLAS or CMS: ~ $(200\mathrm{m})^2$

# FASER



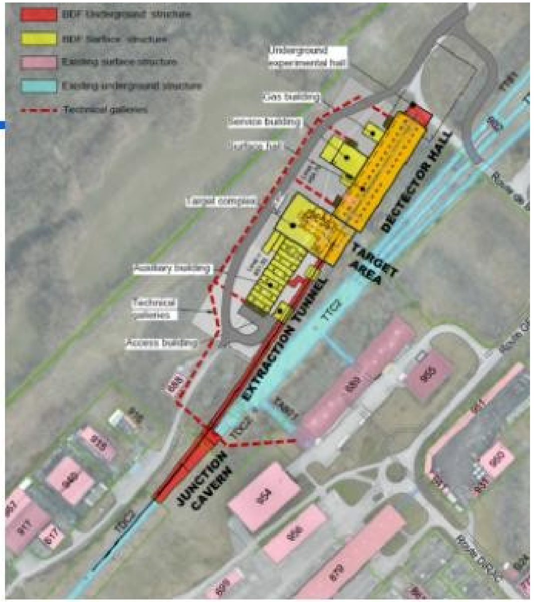
- Approved to take data in Run3, to look for dark photons, dark Higgs, HNL, etc.
- Small detector in the tunnel, with tracker in a magnetic field and calorimeter.

# A different approach: the beam dump

- If the new particles are light and weakly interacting, then the LHC may not be the best place to look for them
- Instead, send protons from CERN's SPS to an absorber: 500 kW is 4x1E13 protons/7 s ->2E20 in 5y

- HS particles produced by mesons (mainly charm) decays; need to absorb all SM decay products to minimise BG → heavy material thick target, with wide beam to dilute energy deposition (different from neutrino facility)
- Muons cannot be absorbed by target: muon shield, possibly magnetised
- Long decay tunnel away from external walls to minimise rescattering of muons and neutrons close to detector
- Vacuum in decay tunnel to reduce neutrino interactions
- Far-away detector with good PID and resolutions

# The SHiP experiment

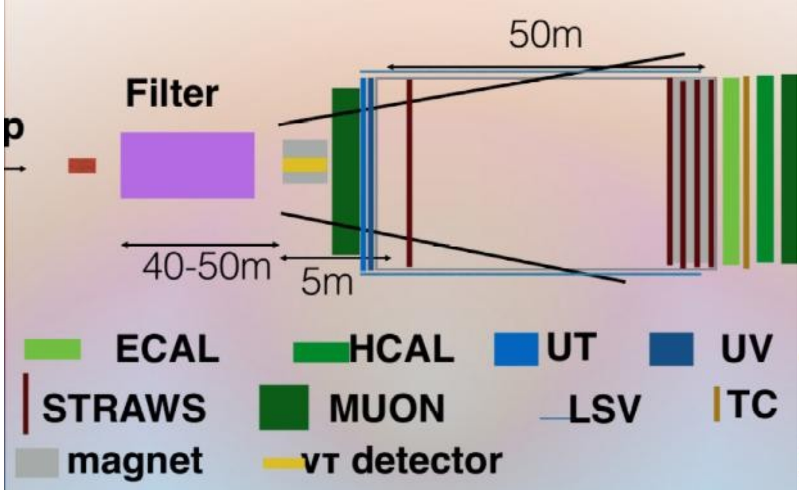


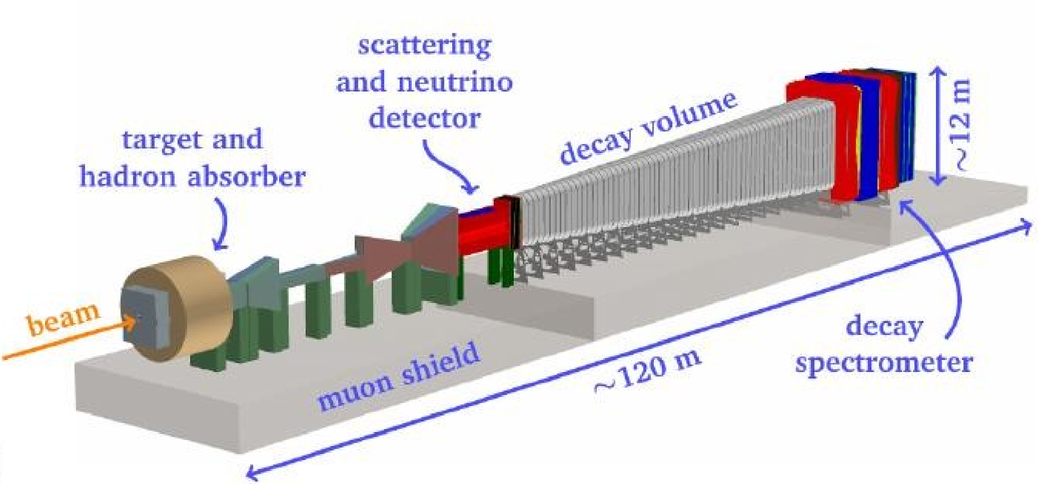
Dedicated detector for weakly coupled long-lived particles, plus tau neutrino and LDM scattering, to be run at future beam-dump facility at CERN.

The spectrometer is located ~100m

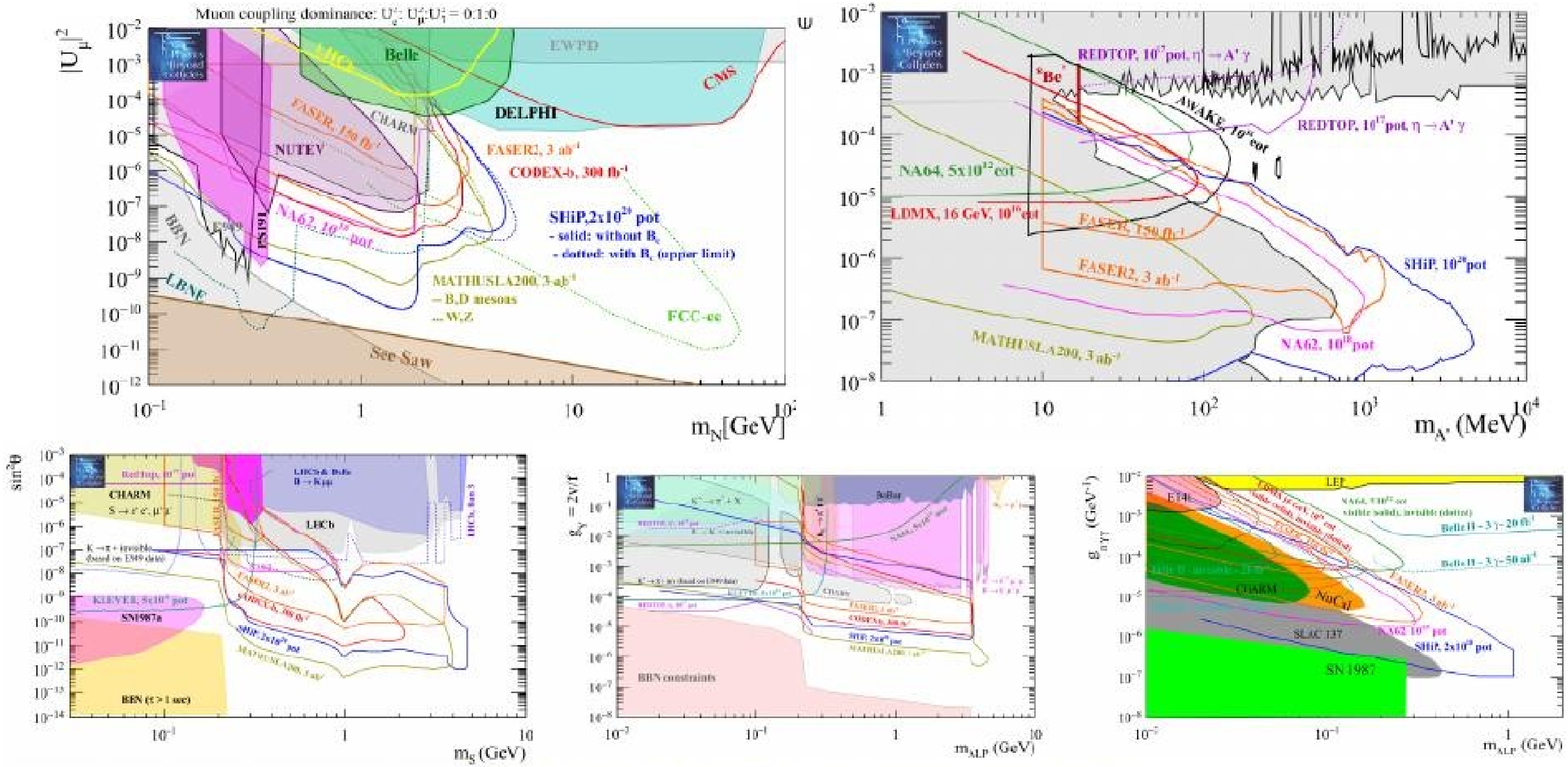
downstream of the target, after a magnetised muon shield, the scattering and neutrino detector and a long decay volume

Aim for a 0-BG experiment (2 events → discovery)





# Physics reach



[1504.04956, 1504.04855, 1811.00930, 1901.09966]

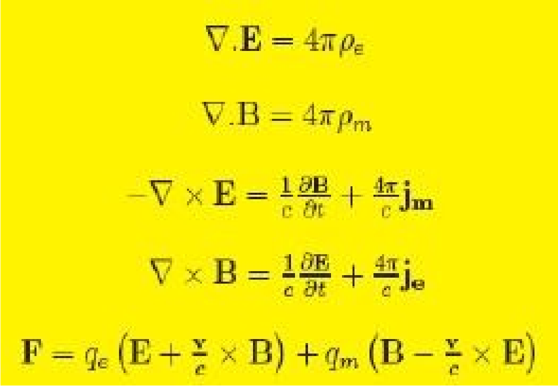
- from top left: HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD), scalar ($K$ and $B$ decays), ALPs coupled to fermions, ALPs coupled to photons

# Monopoles

In classical magnetism, no single magnetic charges

Dirac found that magnetic monopoles with q = n 68.5 e explain quantisation of electric charge

Maxwell equations become symmetric!



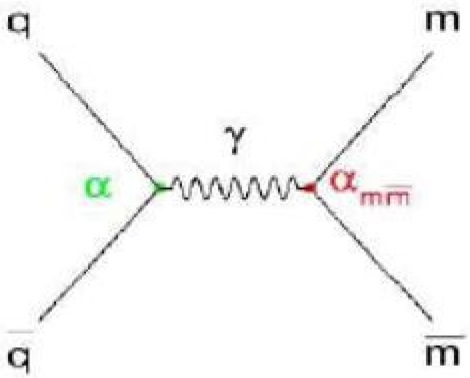
$$\nabla.\mathbf{E} = 4\pi\rho_e$$

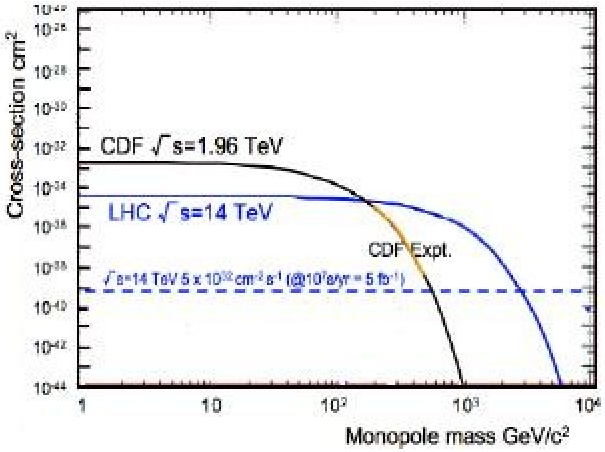
$$\nabla.\mathrm{B} = 4\pi\rho_m$$

$$-\nabla\times\mathbf{E} = \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

$$\nabla\times\mathrm{B} = \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

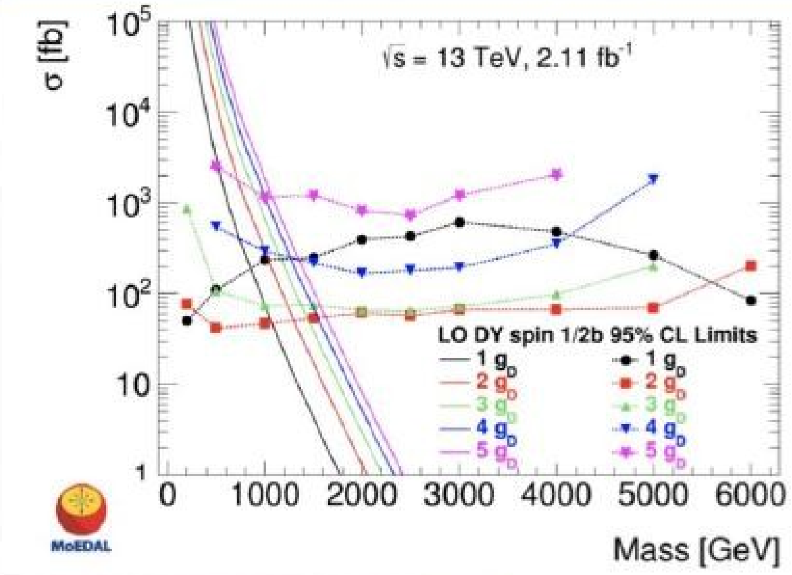
$$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)$$

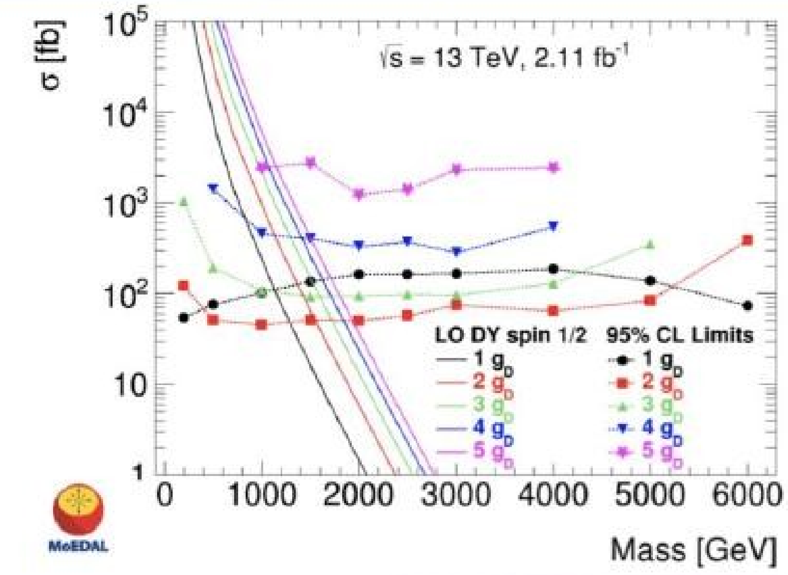


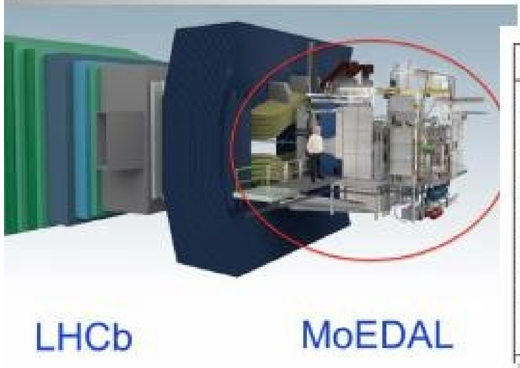


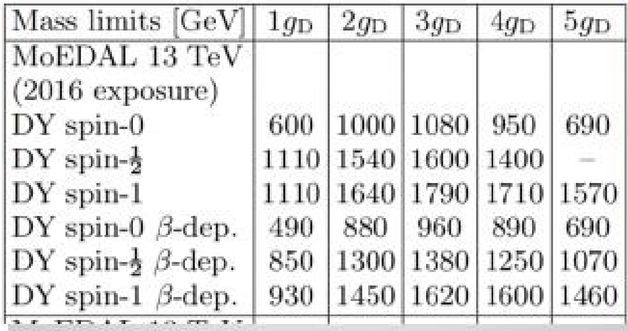
# MoEDAL

2016 data analysis base on 222 kg Aluminium to “stop” the monopoles and search for them with a SQUID precision magnet (2.11fb$^{-1}$) arXiv:1712.09849







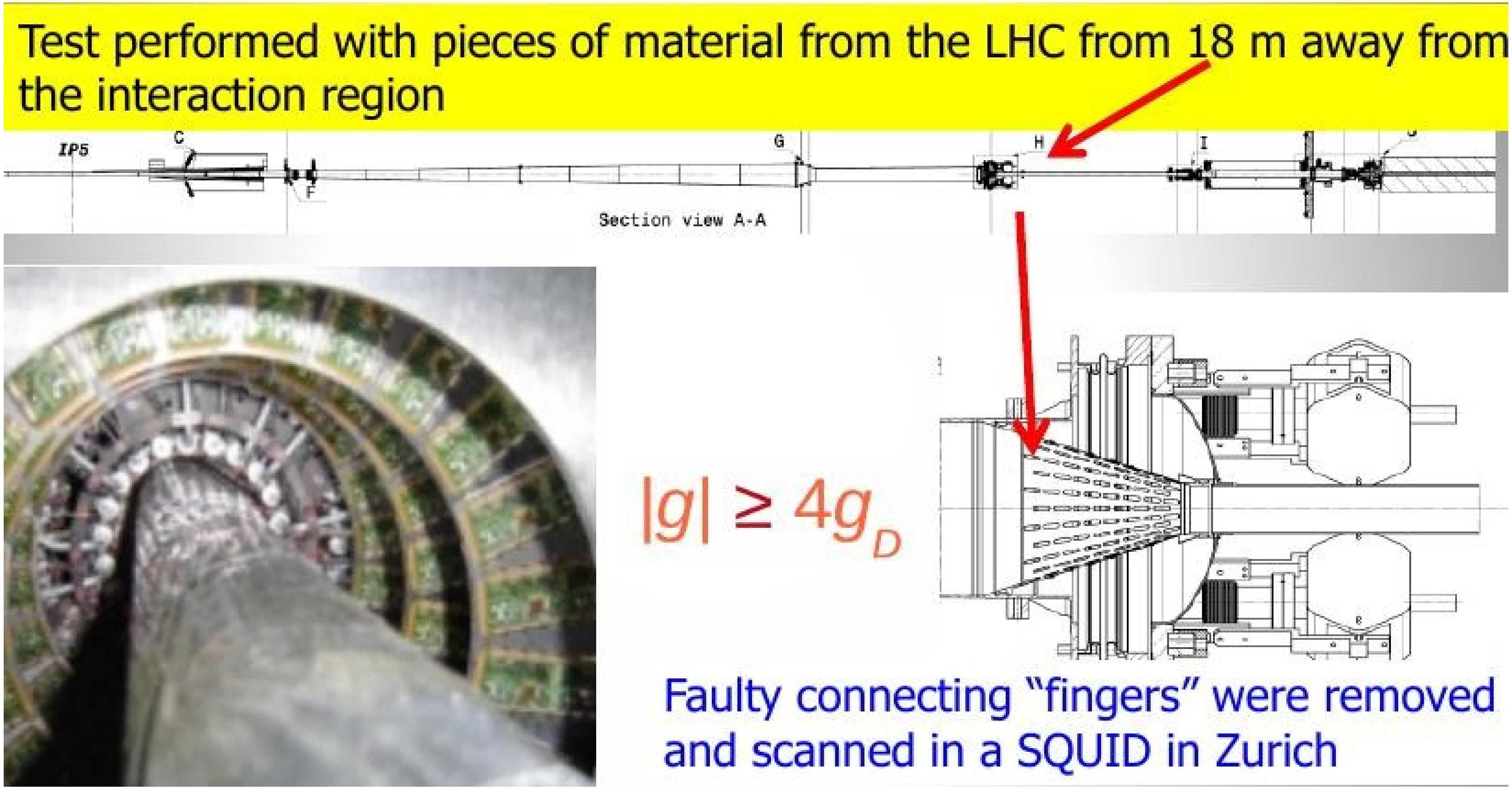


| Mass limits [GeV] | $1g_D$ | $2g_D$ | $3g_D$ | $4g_D$ | $5g_D$ |
|---|---|---|---|---|---|
| MoEDAL 13 TeV (2016 exposure) | | | | | |
| DY spin-0 | 600 | 1000 | 1080 | 950 | 690 |
| DY spin-$\frac{1}{2}$ | 1110 | 1540 | 1600 | 1400 | – |
| DY spin-1 | 1110 | 1640 | 1790 | 1710 | 1570 |
| DY spin-0 $\beta$-dep. | 490 | 880 | 960 | 890 | 690 |
| DY spin-$\frac{1}{2}$ $\beta$-dep. | 850 | 1300 | 1380 | 1250 | 1070 |
| DY spin-1 $\beta$-dep. | 930 | 1450 | 1620 | 1600 | 1460 |

- Limits for different monopole charges

- First monopole search result @LHC at 13 TeV No signal yet..

# Monopoles already in beam pipe?



Test performed with pieces of material from the LHC from 18 m away from the interaction region

$|g| \geq 4g_D$

Faulty connecting “fingers” were removed and scanned in a SQUID in Zurich

Need to destroy beam pipe → wait for end of LHC run

# Conclusions

- The search for “traditional” new physics (SUSY, W’, Z’, sequential or excited fermions etc.) did not lead to discoveries so far
- Need to look everywhere, any many theories predict existence of long-lived particles
- Experimentally challenging, they open a new dimension in particle physics
- Several new experiments proposed to look for them
- It is a relatively new field, so new ideas emerge constantly