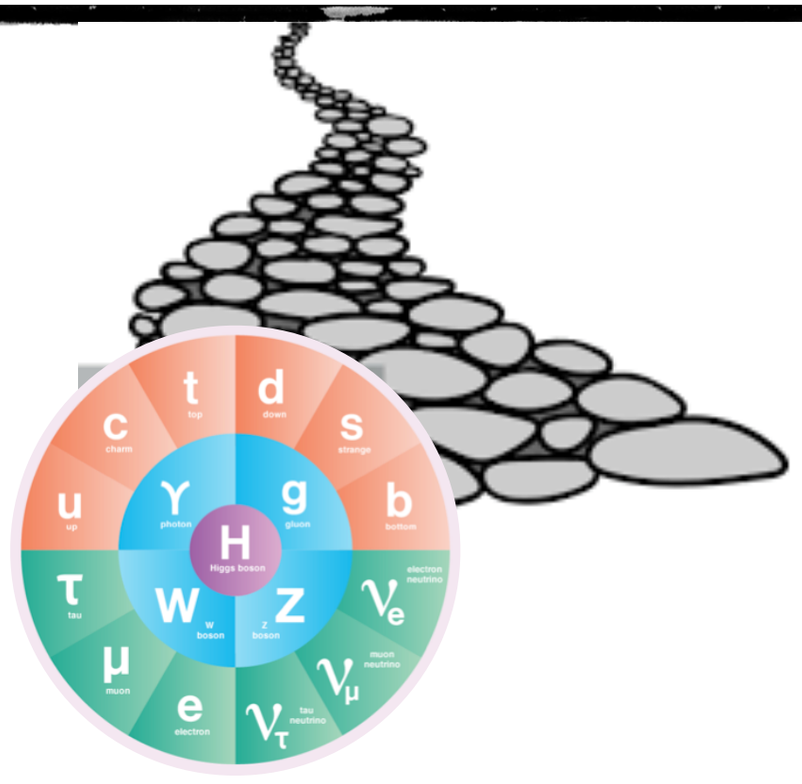
Dark Sectors

Daniele Barducci

WIFAI 2023

Dark Sectors

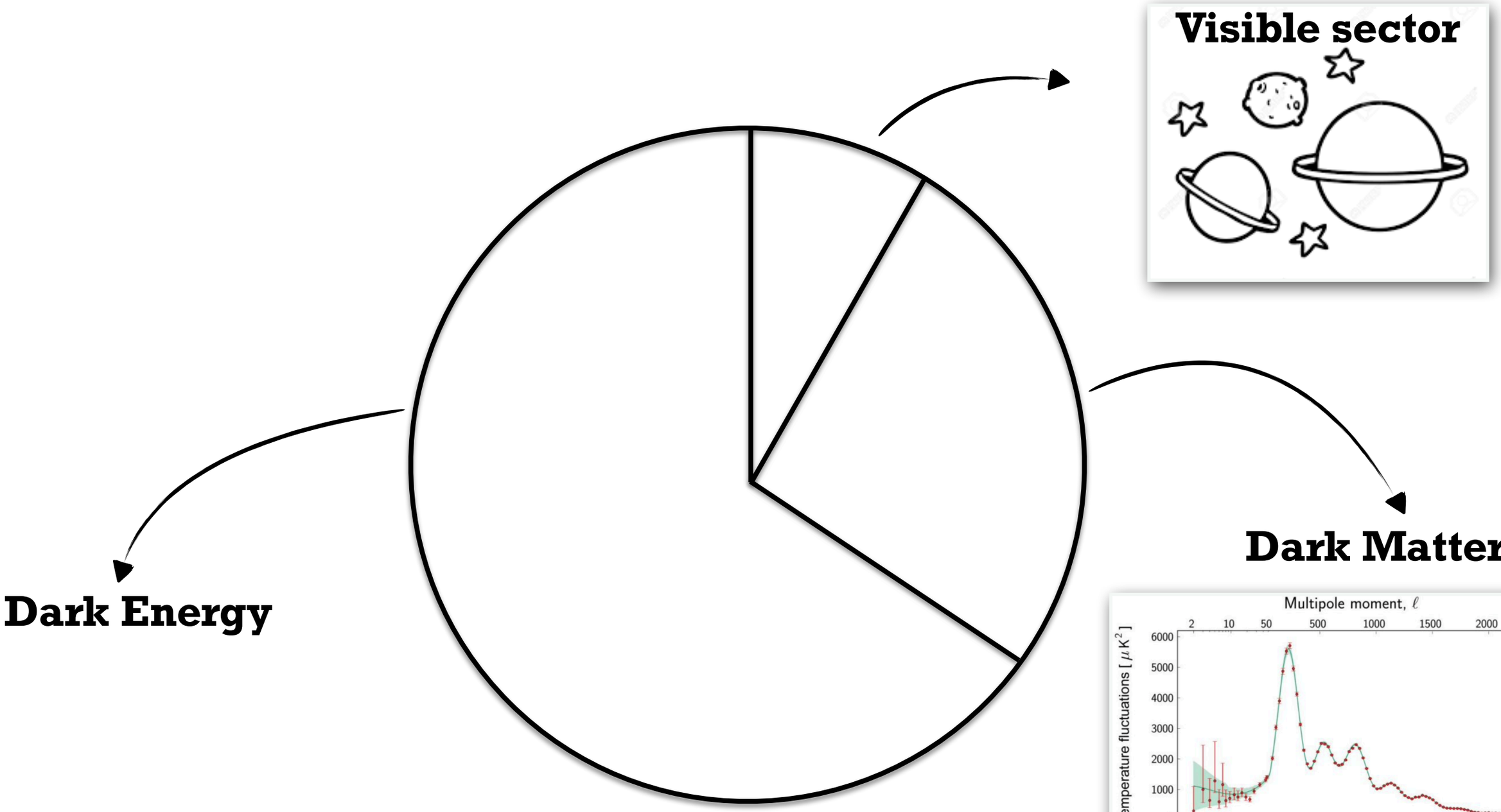


Daniele Barducci

WIFAI 2023

Why Dark Sectors?

- Primary motivation is the experimental evidence for Dark Matter



- Motivates the study of SM extensions with new particles and interactions

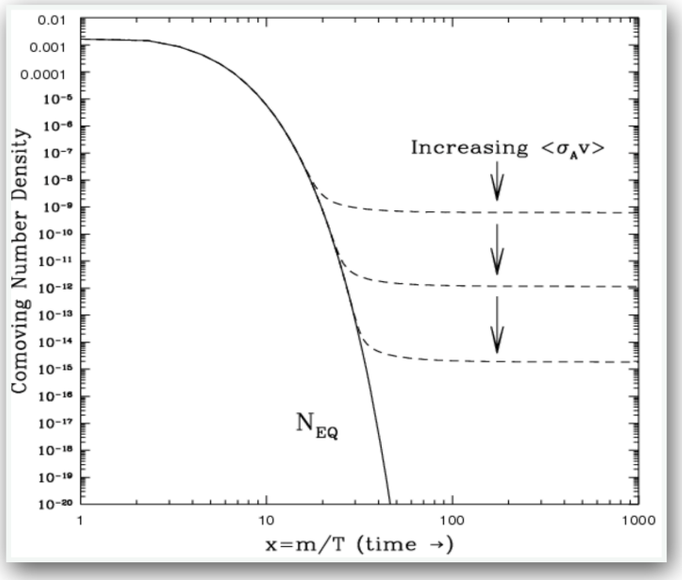
The prime example

- The most common paradigm for Dark Matter is the **WIMP**

New massive particle in thermal equilibrium with the SM in the Early Universe

Decouples at $T_\chi \sim m_\chi$, it's abundance freezes-out

- Reproducing relic abundances fixes the interaction to be electroweak-like



$$\Omega h^2 \sim 0.1 \frac{\text{pb}}{\langle \sigma v \rangle}$$

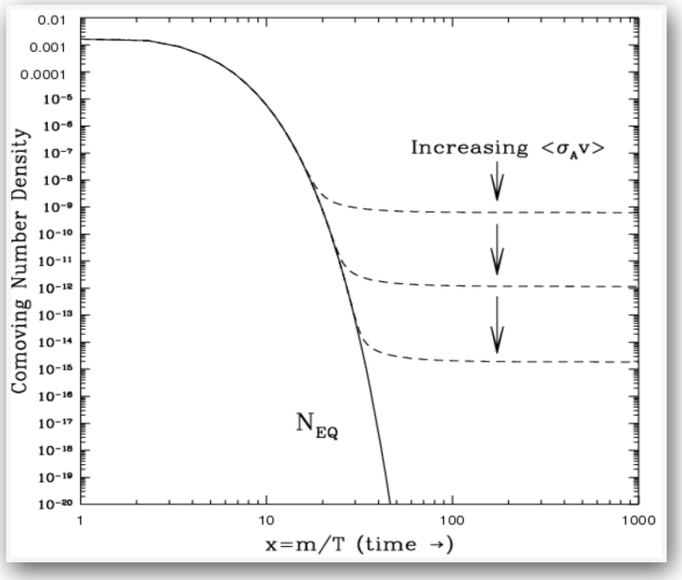
The prime example

- The most common paradigm for Dark Matter is the **WIMP**

New massive particle in thermal equilibrium with the SM in the Early Universe

Decouples at $T_\chi \sim m_\chi$, it's abundance freezes-out

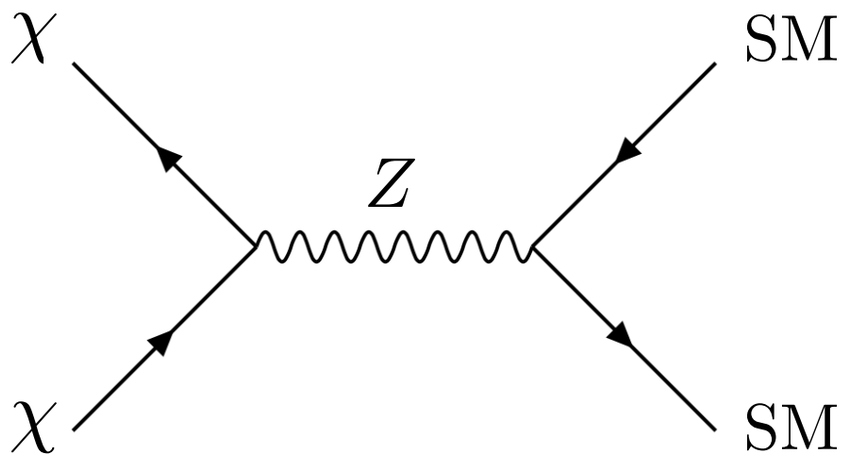
- Reproducing relic abundances fixes the interaction to be electroweak-like



$$\Omega h^2 \sim 0.1 \frac{\text{pb}}{\langle \sigma v \rangle}$$

What's in here?

- **Assumption -** Dark Matter interacts with the SM via EW interactions



$$\langle \sigma v \rangle \simeq 1 \text{ pb} \left(\frac{\alpha_W}{10^{-2}} \right)^2 \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

EW scale mass

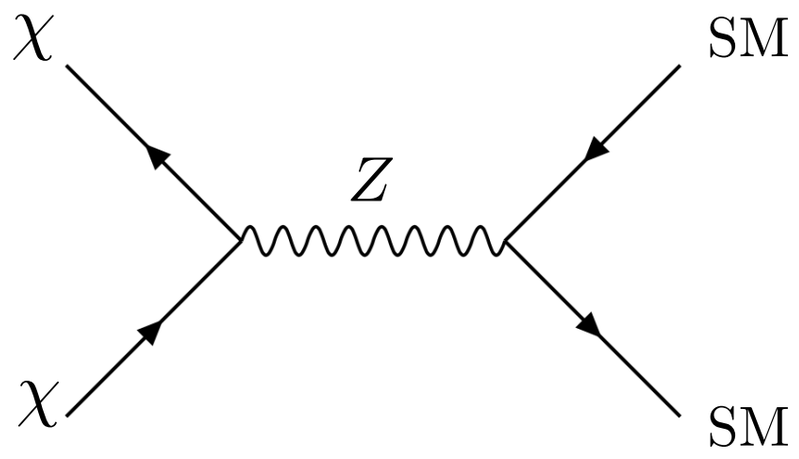
EW scale coupling

- TeV scale particle with EW coupling gives the right relic abundance

WIMP miracle

Can one have a WIMP lighter than few GeV produced via thermal freeze-out ?

Light state

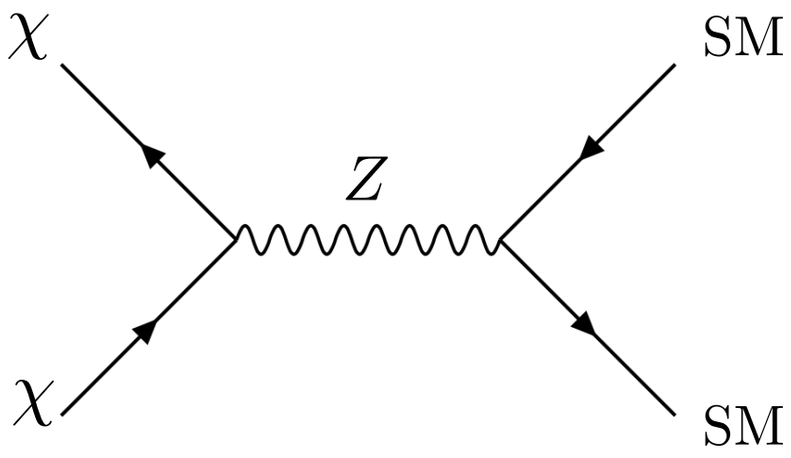


$$m_\chi \gtrsim \text{GeV}$$

$\langle \sigma v \rangle \sim 1 \text{ pb} \left(\frac{m_\chi}{3 \text{ GeV}} \right)^2$ - DM is overproduced $\quad \Omega h^2 \gg \Omega h^2_{\text{exp}}$ **Lee - Weinberg bound**

Can one have a WIMP lighter than few GeV produced via thermal freeze-out ?

Light state



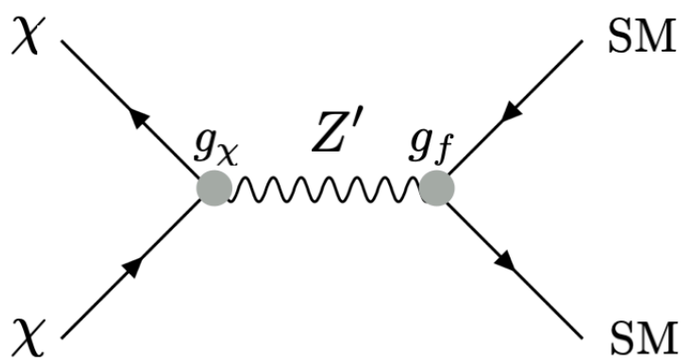
$m_\chi \gtrsim$ GeV

$\langle \sigma v \rangle \sim 1$ pb $\left(\frac{m_\chi}{3\ \mathrm{GeV}}\right)^2$ - DM is overproduced $\quad \Omega h^2 \gg \Omega h^2_{\mathrm{exp}}$ **Lee - Weinberg bound**

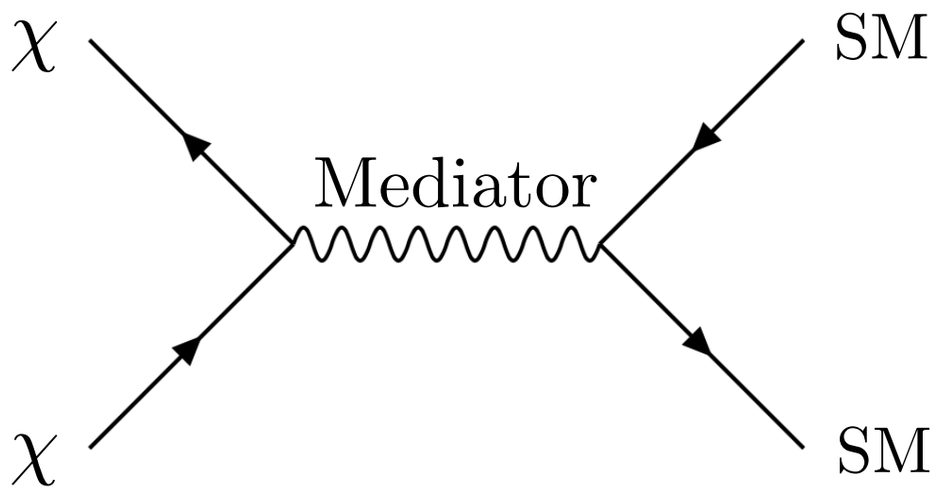
- Assume a new mediator $\mathcal{L} \sim Z'_\mu \left(g_\chi \bar{\chi} \gamma^\mu \chi + g_f \bar{f} \gamma^\mu f \right)$

$$\langle \sigma v \rangle \sim \ 1\,\mathrm{pb} \times \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{0.001}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{Z'}}\right)^4$$

- DM can be lighter if the mediator is a (light) BSM state



Relax the assumption on the mediator - allow it to be a BSM state



- Two different approaches to investigate this paradigm

Complete theory

SUSY, extra dimensions…

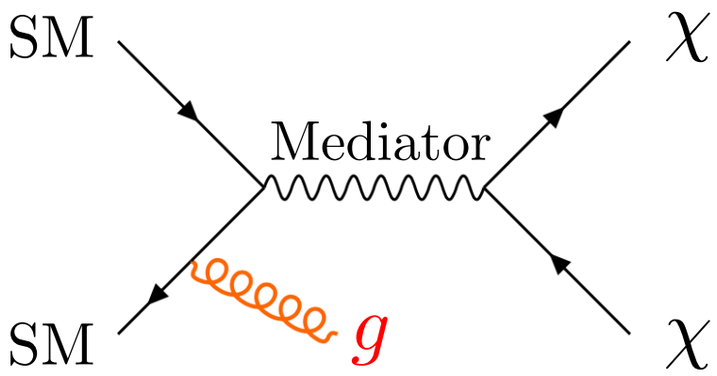
- Not model independent ✗
- More predictive (correlations…) ✓
- Solve other open problems ✓

Simplified models

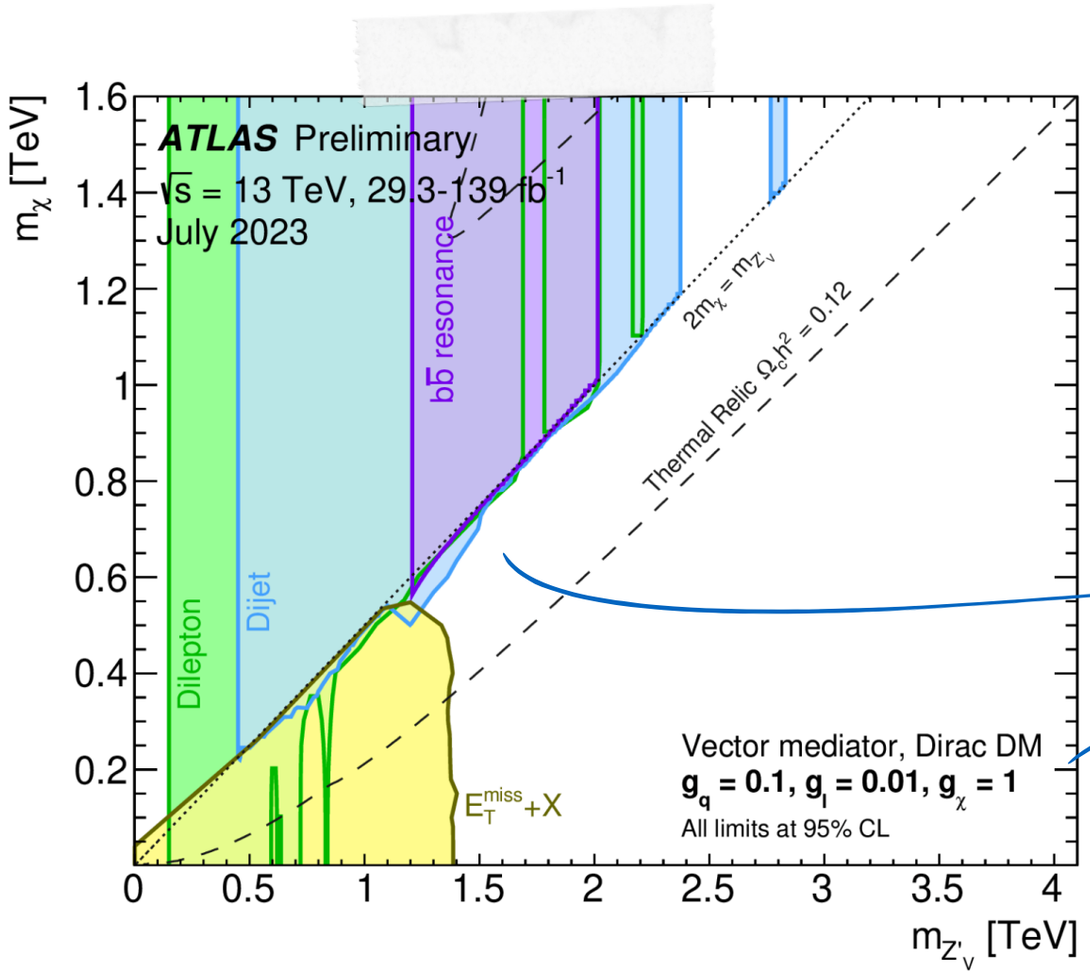
Assume DM and mediator

- Model independent ✓
- Less predictive ✗
- Less ambitious ✗

- For LHC high - p_T searches the community has shifted more to the 2^{nd} approach
- Invisible decay of the mediator are targeted via **mono-X channels** [Abdallah+ 1506.03116]

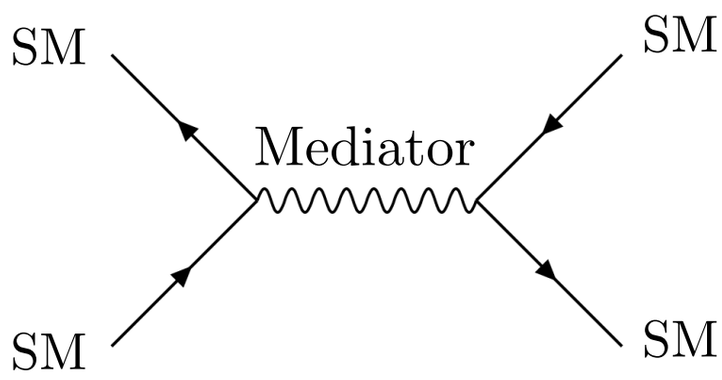


$$\begin{cases} j + E_T^{\text{miss}} \\ \gamma + E_T^{\text{miss}} \\ Z + E_T^{\text{miss}} \\ \dots \end{cases}$$



Ωh^2 line to be taken with care

Visible decays of the mediator can be tested

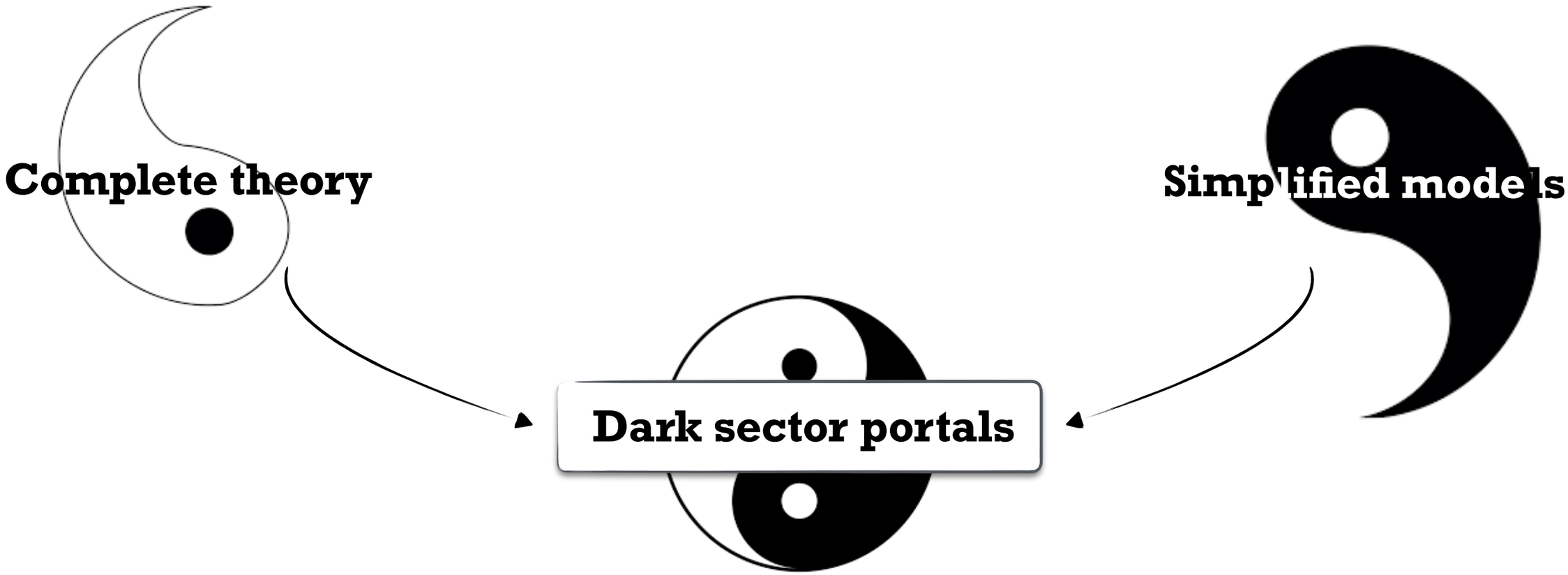


Limits depend on the assumptions

- Results in simplified model can allow for an easy reinterpretation in other theories ✓

Complete theory

Simplified models


Complete theory
Simplified models
Dark sector portals

Dark sector portals

SM visible sector

$B^{\mu\nu}$ q u^c

H ℓ

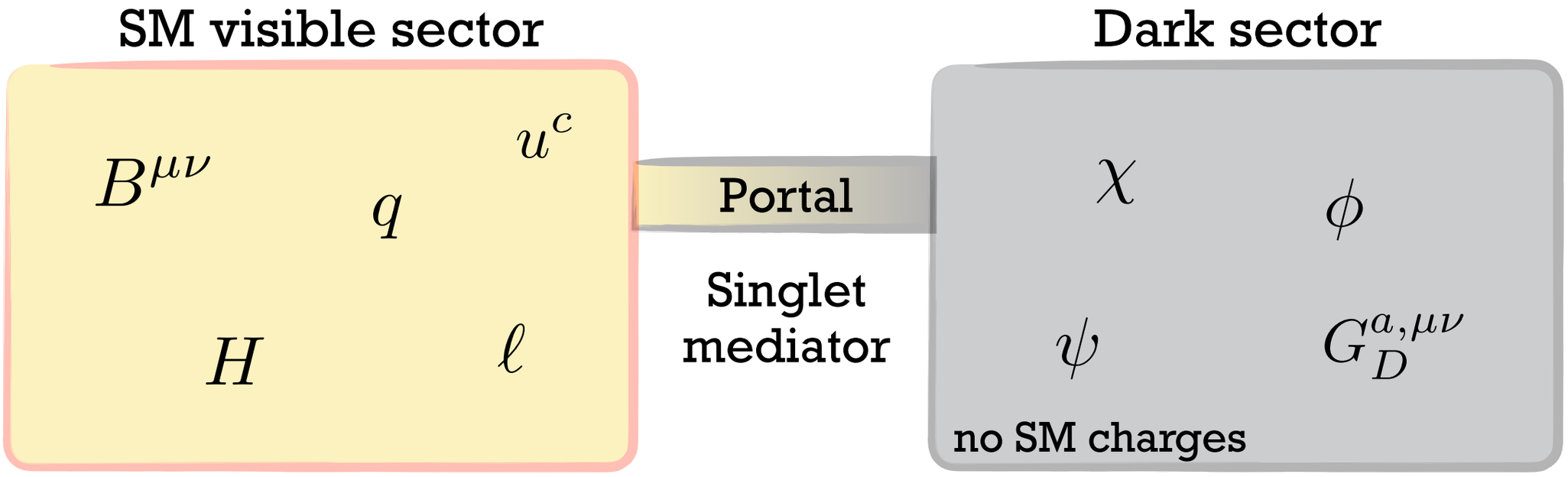
Dark sector

χ ϕ

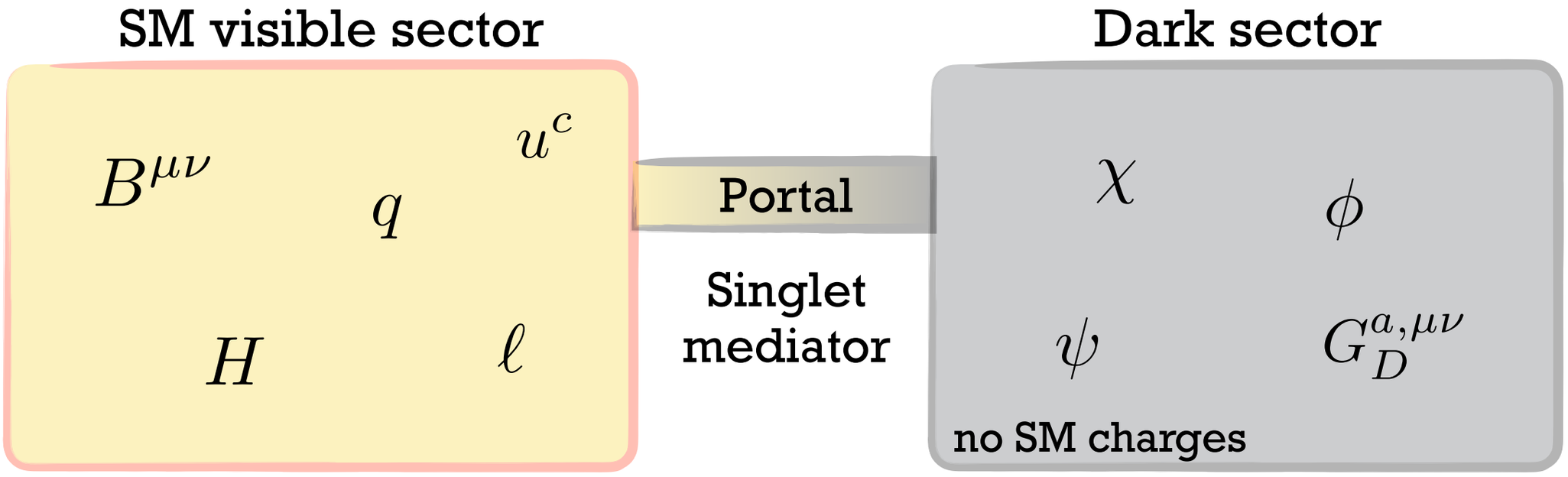
ψ $G_D^{a,\mu\nu}$

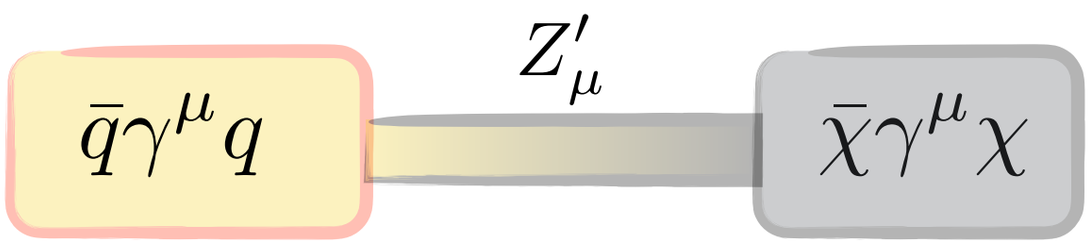
no SM charges

Dark sector portals

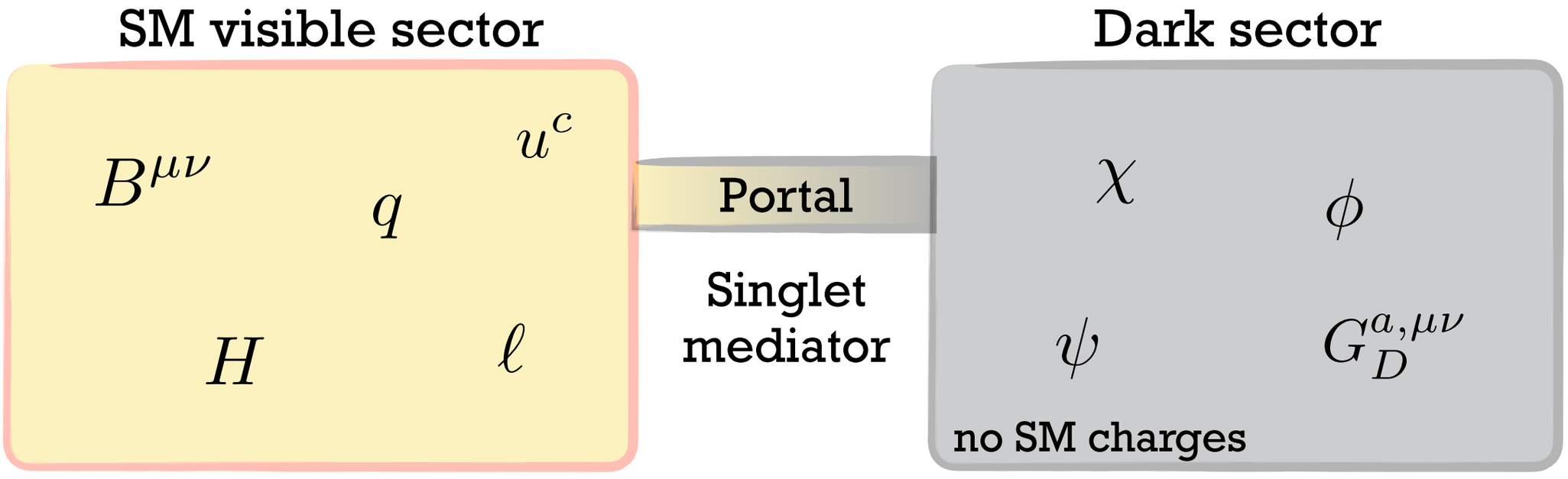


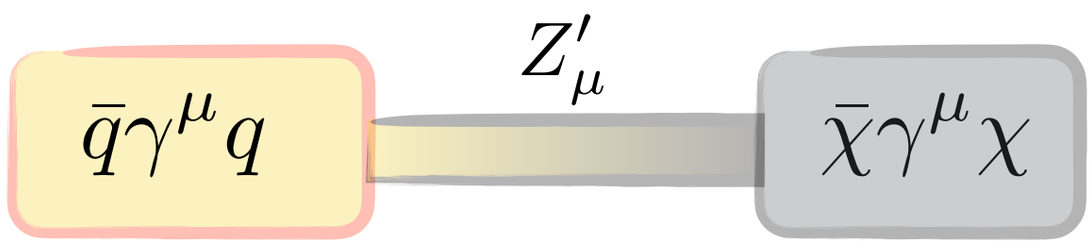
Dark sector portals





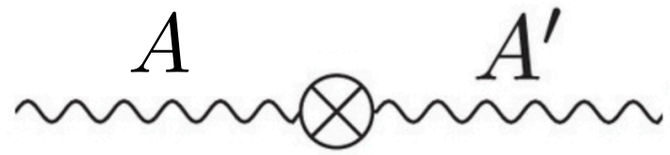
Dark sector portals



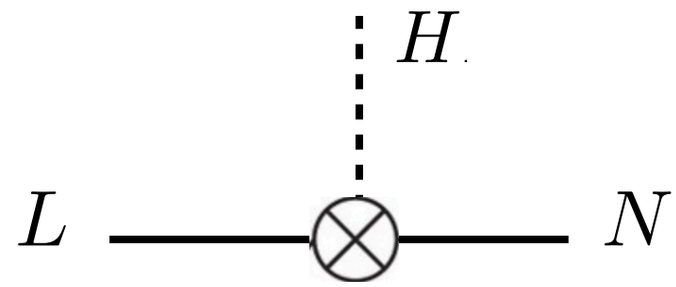


- Assuming “renormalizability”, the number of portal interactions is very limited
- Relaxing this hypothesis allows for more possibility

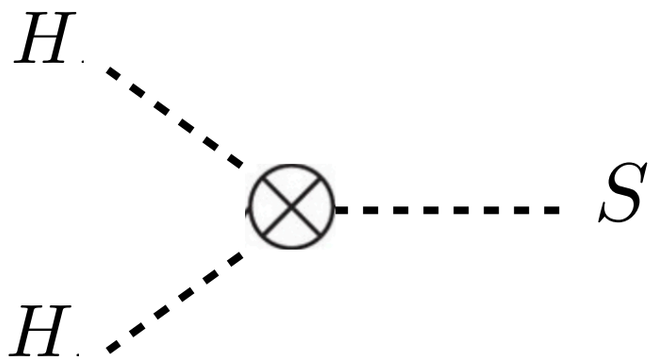
Vector portal $\epsilon F^{\mu\nu} F'_{\mu\nu}$



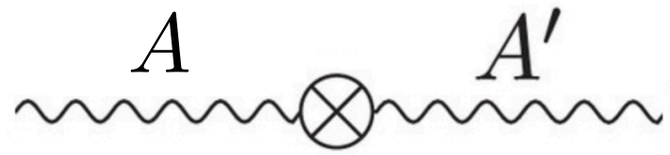
Fermion portal $yLHN$



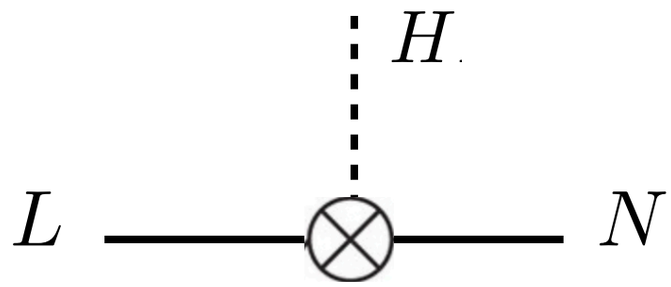
Scalar portal $(\mu S + \lambda S^2) H^\dagger H$



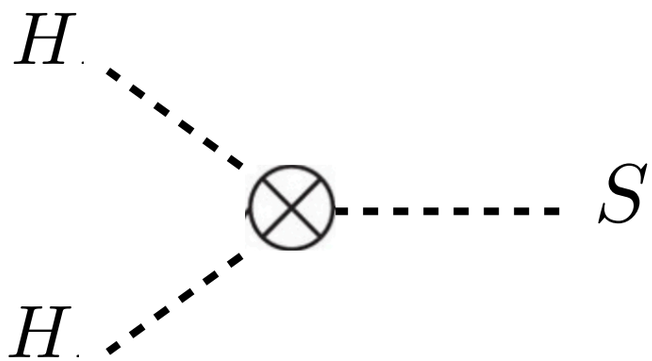
Vector portal $\epsilon F^{\mu\nu} F'_{\mu\nu}$



Fermion portal $yLHN$

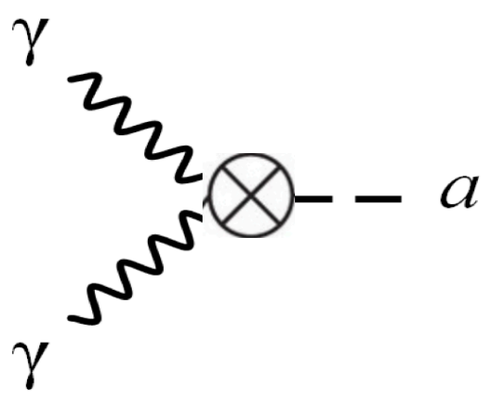


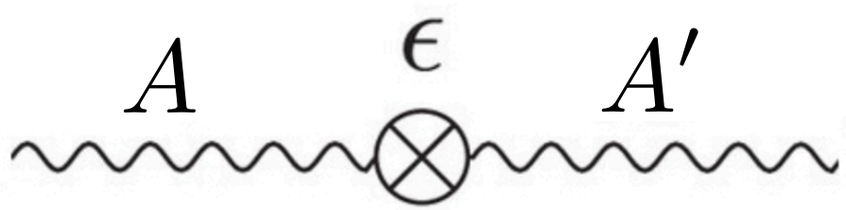
Scalar portal $(\mu S + \lambda S^2) H^\dagger H$



- A $d > 4$ there is a special case, the axion portal

Axion portal $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$




A
ϵ
A′

Vector portal - the dark photon

- New abelian gauge boson from a $U(1)_d$ gauge group [Fayet '80, Okun '82, Holdom '86]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + \boxed{\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu}} - \frac{1}{2} m^2_{A'} A'_{\mu} A'^{\mu}$$

- Massless dark photons doesn't interact with the SM at $d = 4$ [Dobrescu 0411004]
- Massive dark photon can be DM if light and non thermal [Nelson+ 1105.2812, Arias+ 1201.5902] or produced during inflation [Graham+ 1504.02102, Nakai+ 2004.10743]
- Different origins for $m_{A'}$ can modify cosmological history [Redi & Tesi 2204.14274]

Vector portal - the dark photon

- New abelian gauge boson from a $U(1)_d$ gauge group [Fayet '80, Okun '82, Holdom '86]

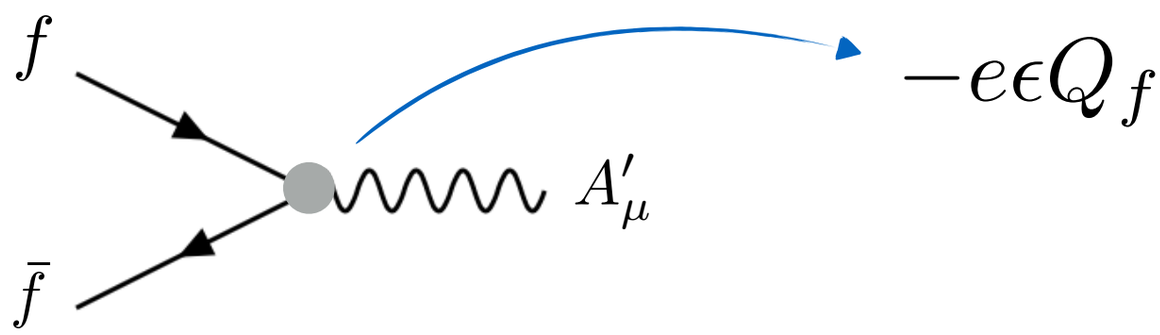
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + \boxed{\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu}} - \frac{1}{2} m^2_{A'} A'_\mu A'^\mu$$

- Massless dark photons doesn't interact with the SM at $d = 4$ [Dobrescu 0411004]
- Massive dark photon can be DM if light and non thermal [Nelson+ 1105.2812, Arias+ 1201.5902] or produced during inflation [Graham+ 1504.02102, Nakai+ 2004.10743]
- Different origins for $m_{A'}$ can modify cosmological history [Redi & Tesi 2204.14274]

Massive dark photon

- The dark photon inherits a coupling to the SM currents

$$\mathcal{L} \supset -e\,\varepsilon J^\mu A'_\mu$$



- Dark photons can be produced as normal photons
- Simple pheno, two dimensional parameter space $m_{A'}, \varepsilon$ - Good for exp. searches
- Coupling to DM adds g_χ, m_χ - Invisible decay channels

- Search strategies depend on the dark photon decay mode

$$2m_e \simeq 1\ \text{MeV}$$

Invisible decay or stable

$$\Gamma \sim \frac{1}{3}\alpha_D\, m_{A'}\sqrt{1-\frac{4m_\chi^2}{m_{A'}^2}}\left(1+\frac{2m_\chi^2}{m_{A'}^2}\right)$$

Visible dark photon

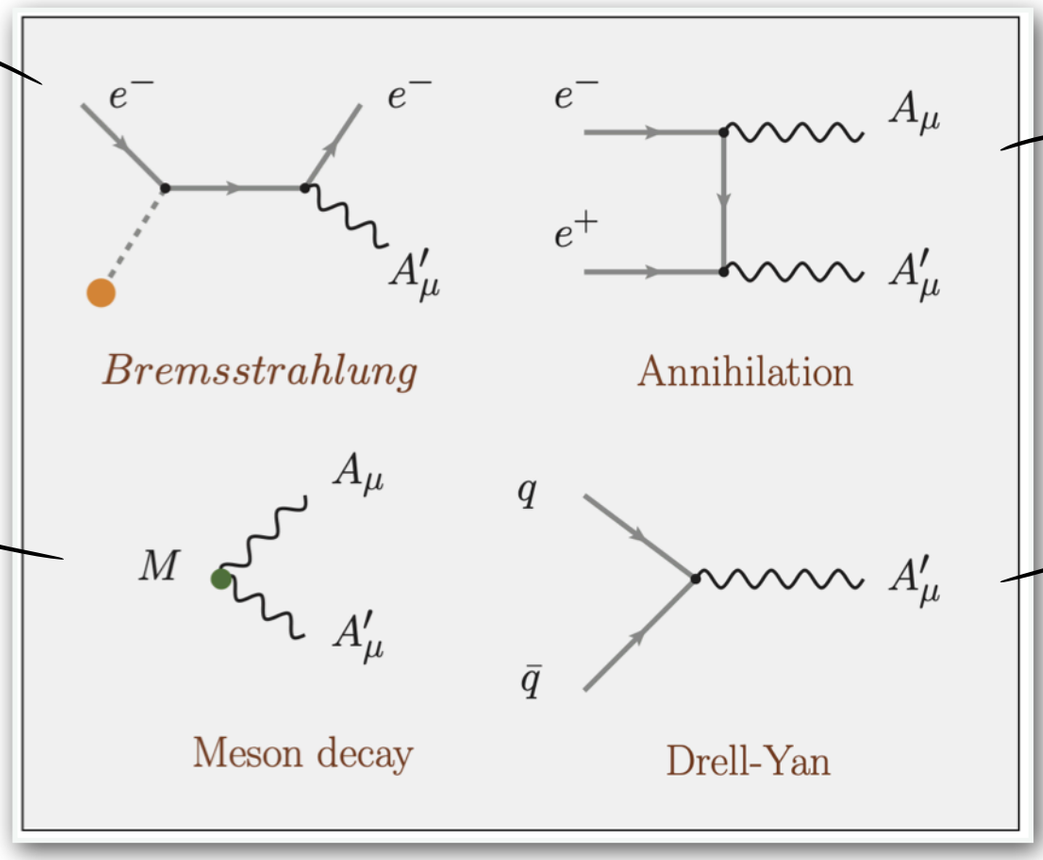
$$\Gamma \sim \frac{1}{3}\alpha\,\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$

$$L_{\text{lab}} \sim 0.1\ \text{m}\left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2\left(\frac{10^{-5}}{\epsilon}\right)^2\left(\frac{E_{A'}}{\text{GeV}}\right)$$

The dark-photon can be long lived

Beam-dump

Small ϵ
Light A'

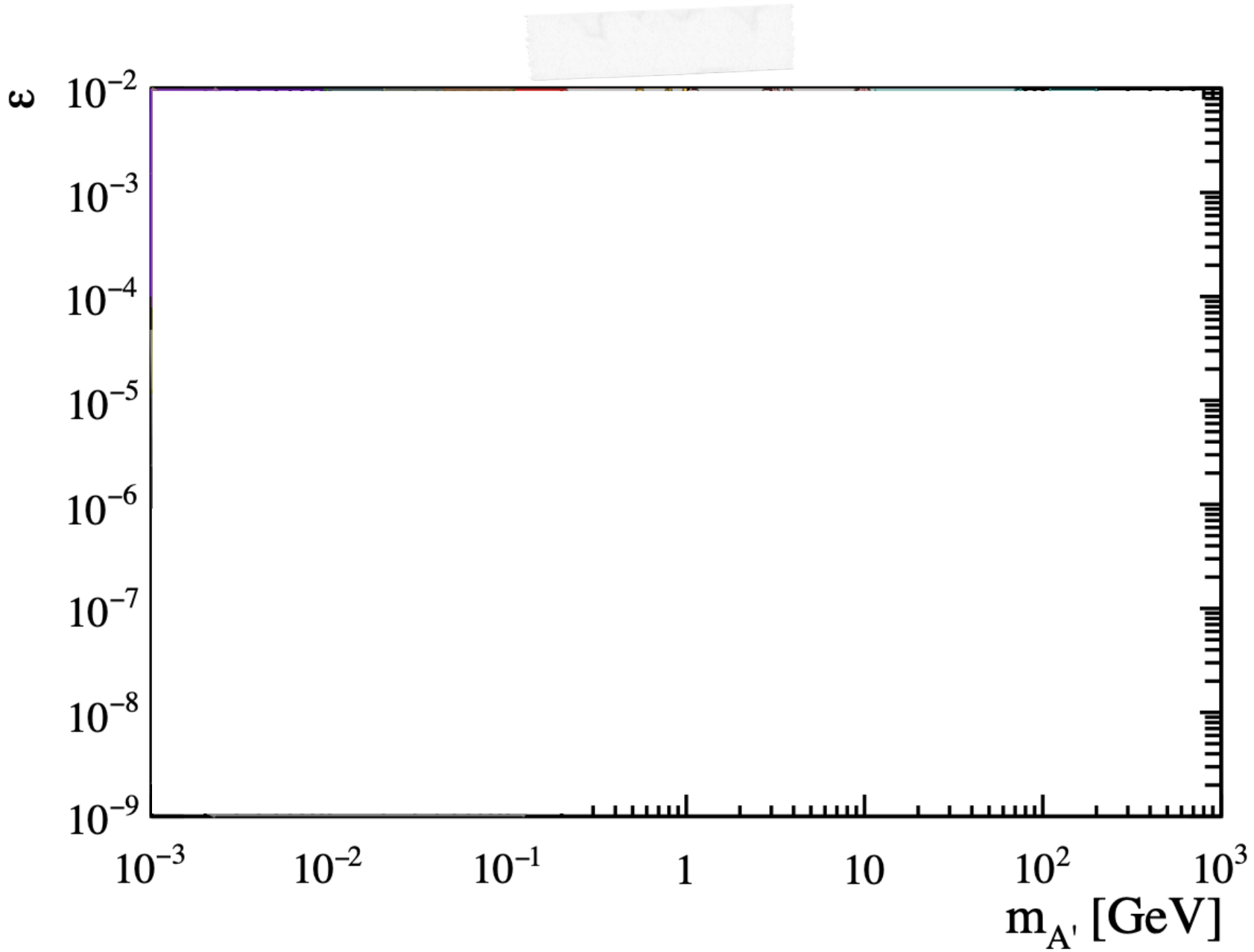


Collider

Higher ϵ
Heavier A'

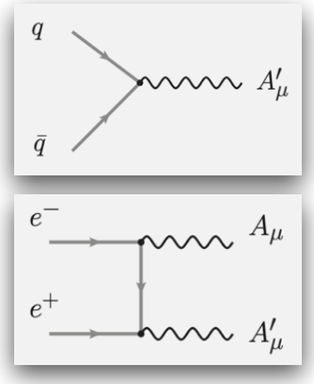
Visible final states $A' \to \ell^+\ell^-$

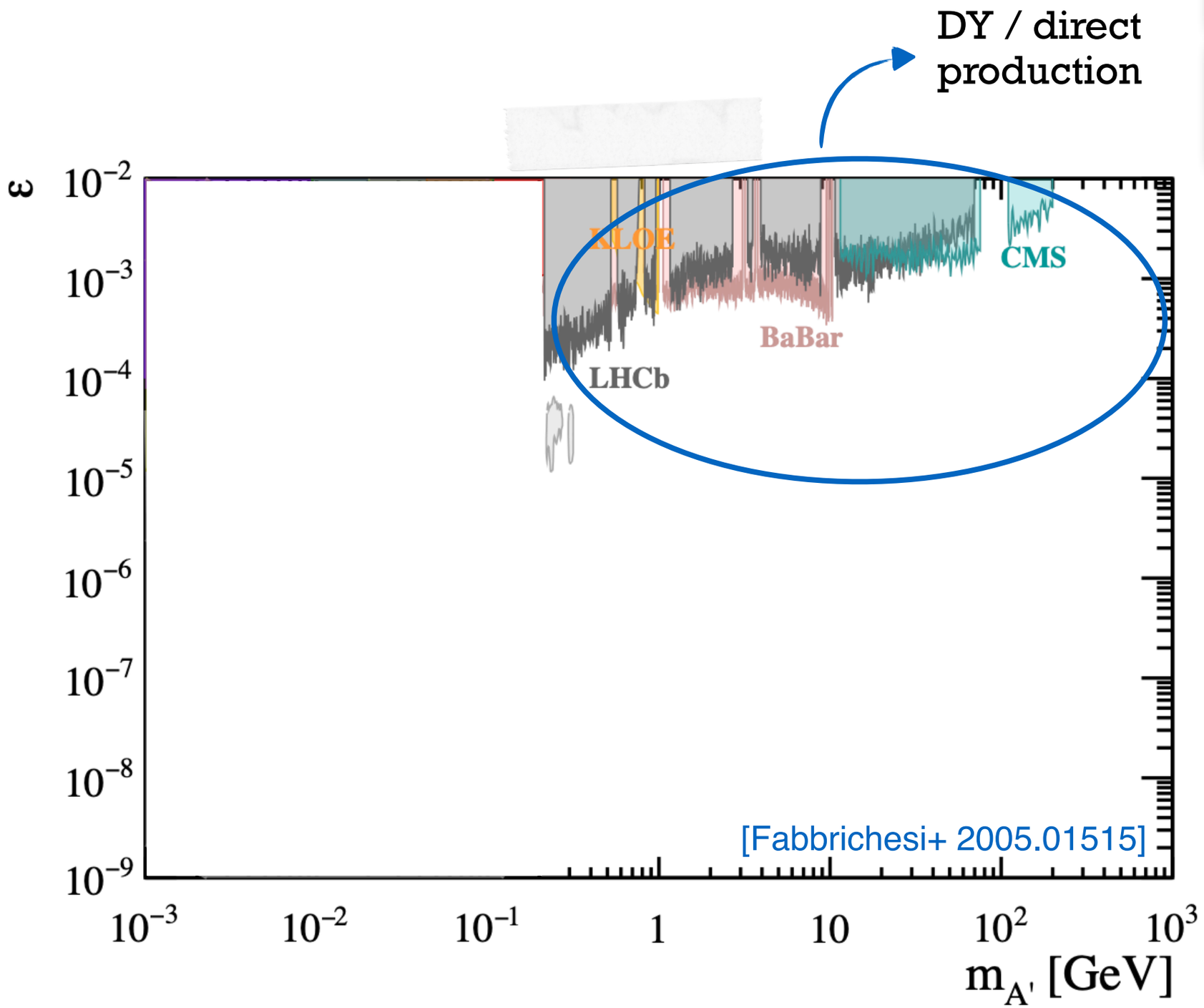
- Search for bumps in $\ell^+\ell^-$ invariant mass



Visible final states $A' \to \ell^+\ell^-$

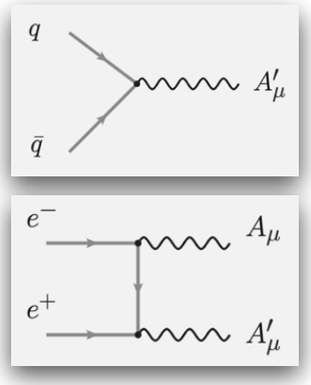
- Search for bumps in $\ell^+\ell^-$ invariant mass





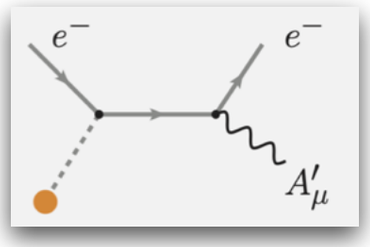
Visible final states $A' \to \ell^+\ell^-$

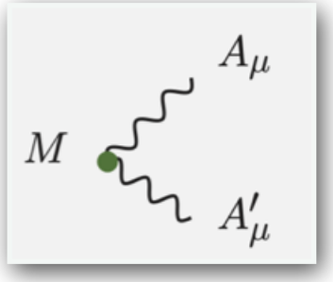
- Search for bumps in $\ell^+\ell^-$ invariant mass

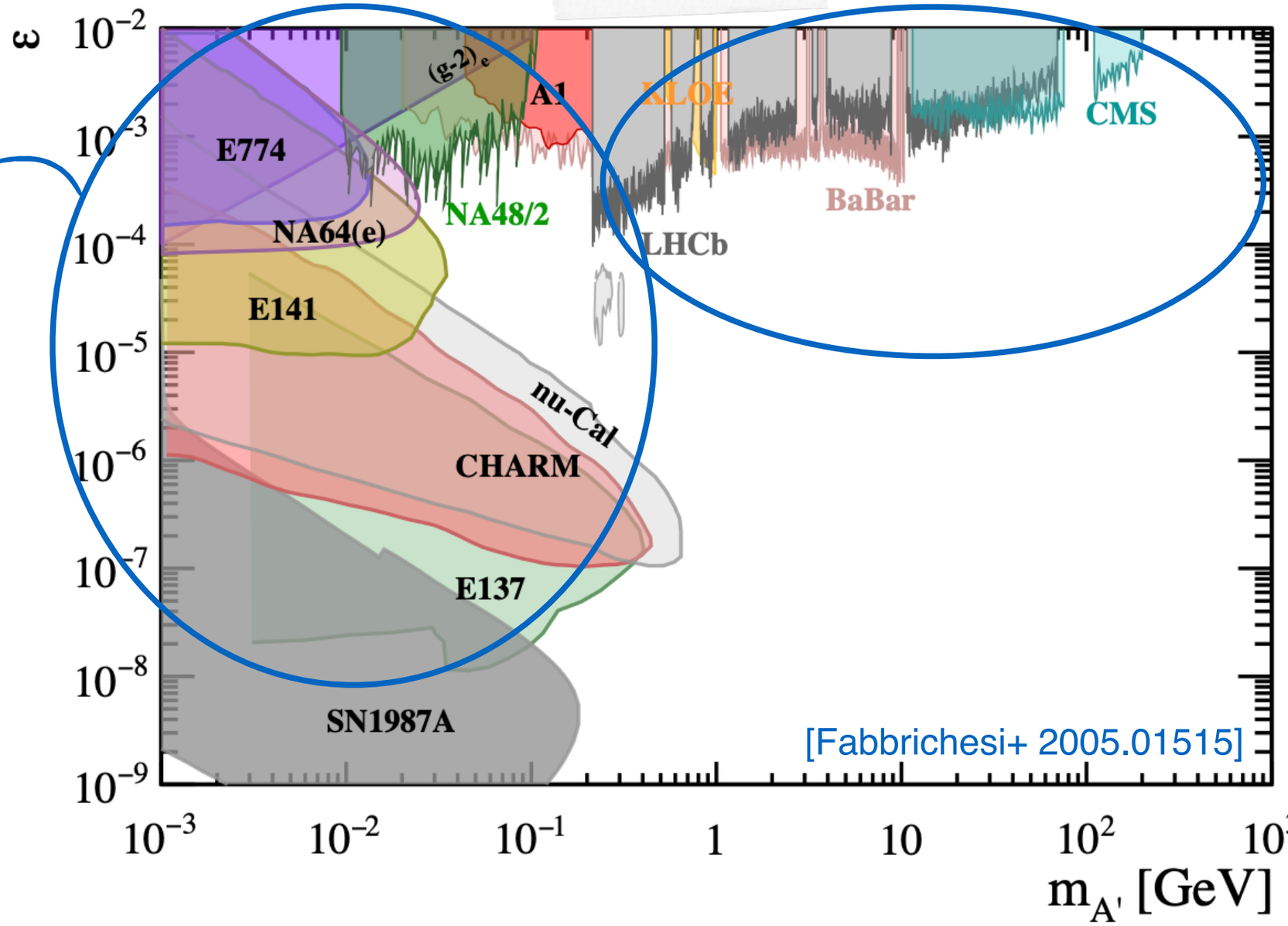


DY / direct production

Beam-dump

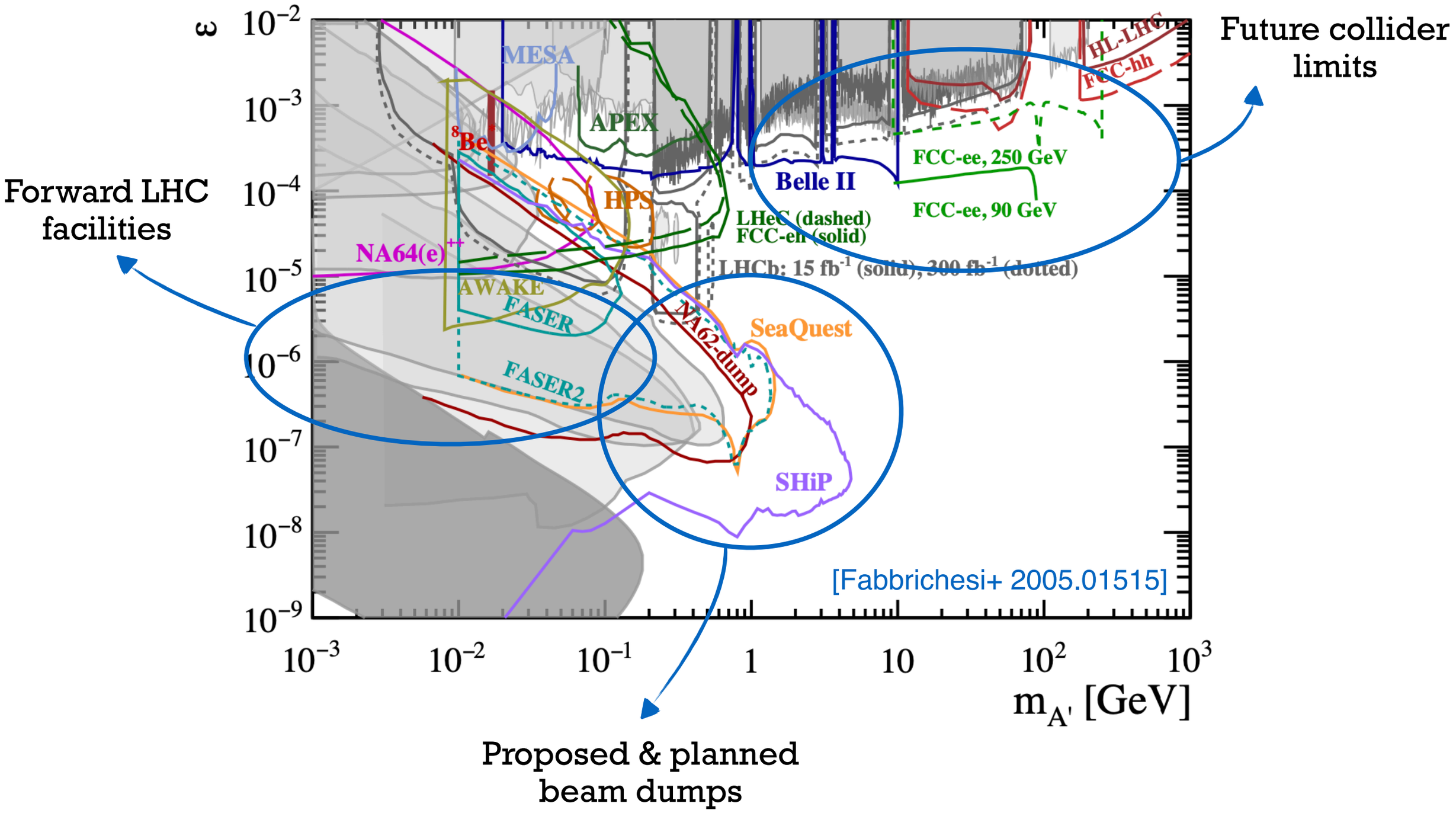






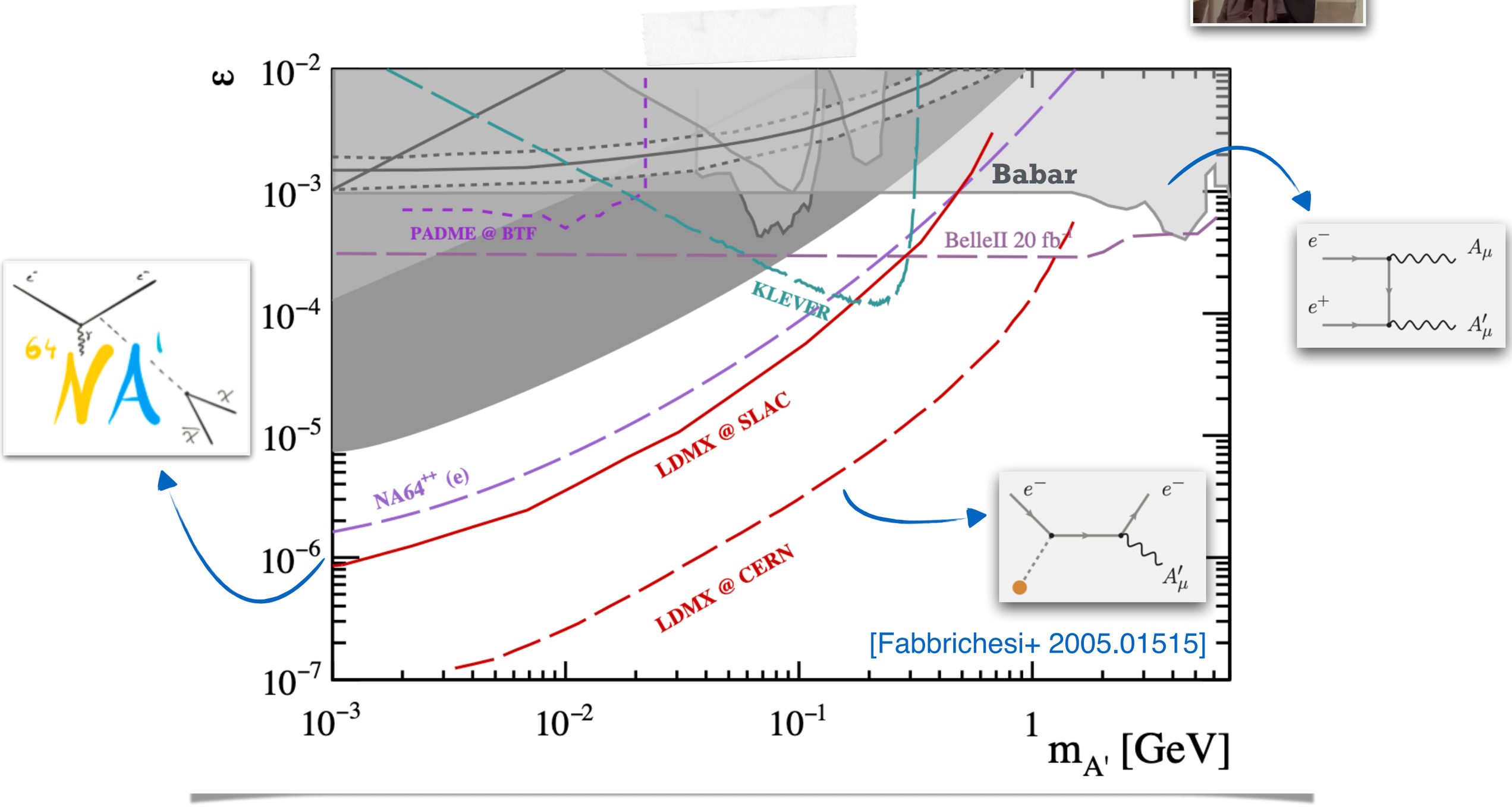
[Fabbrichesi+ 2005.01515]

Visible final states $A' \to \ell^+\ell^-$

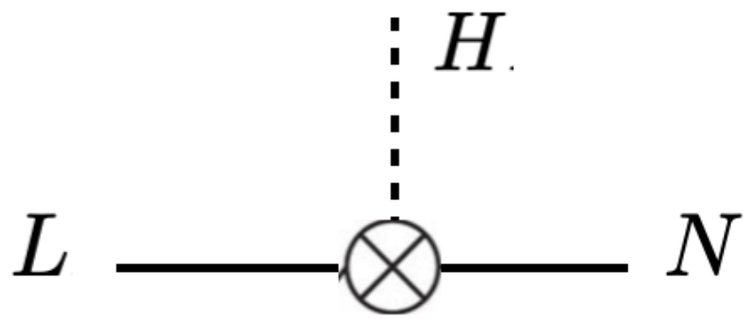


Invisible final states $A' \to \chi\chi$

- Search for missing energy, missing momentum, missing mass…



- For smaller $m_{A'} \lesssim 1\ \mathrm{MeV}$ strong bound from astrophysics and cosmology


H
L
N

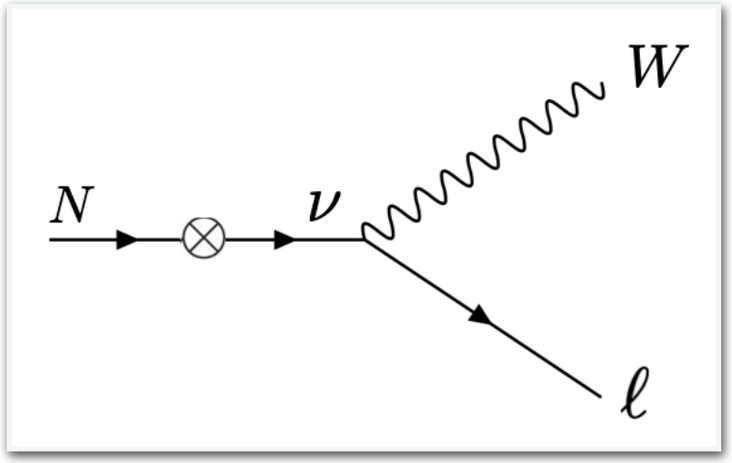
Fermion portal - the sterile neutrino

- A new fermion singlet can account for non zero neutrino masses
  [Minkowsky '77, Yanagida '79, Mohapatra+ '80]

$$\mathcal{L} \sim yLHN + \frac{1}{2}MN^2 \qquad m_{\nu,N} \sim \begin{cases} y^2v^2/M \\ M \end{cases}$$

- Sterile neutrino interacts with the SM via mixing

$$\theta \sim \frac{yv}{m_N} \sim \sqrt{\frac{m_\nu}{m_N}} \ll 1$$



$$\Gamma \sim \frac{1}{192\pi^3}\theta^2\frac{m_N^5}{m_W^4}$$

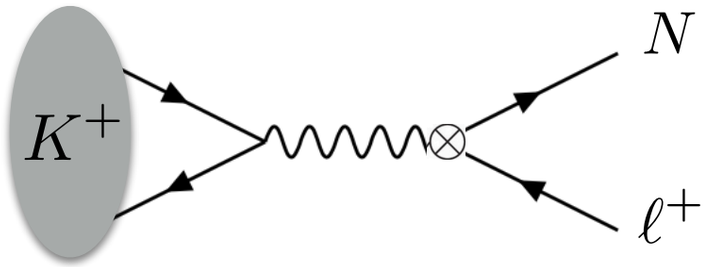
- Suppressed interaction with the SM model

$$\begin{cases} \text{Small production rates} \\ \text{Lab decay length can be macroscopic} \end{cases} \qquad L_{\text{lab}} \sim 5\ \text{m}\left(\frac{\text{GeV}}{m_N}\right)^6\left(\frac{10^{-2}}{\theta}\right)^2\frac{E_N}{10\ \text{GeV}}$$

Sterile neutrino portal is the ideal dark sector prototype

- Sterile neutrinos are produced in processes with an active neutrino, with a θ^2 rescaling
- Production mode and search strategy depend on the mass and decay pattern

Meson decay

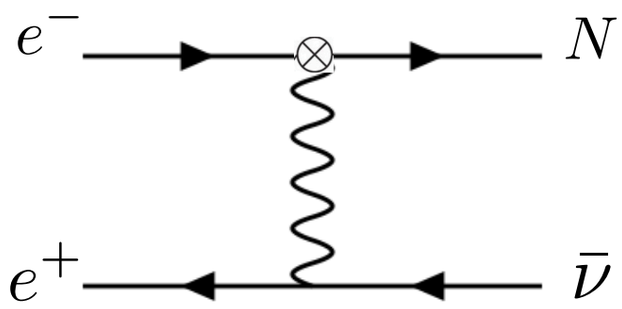


- Or $K^+ \to \pi^0 \ell^+ N$

- **Mass reach limited by meson mass**
- **High-intensity at beam-dump**
- **Possible sensitivity to longer lifetime with far facilities**

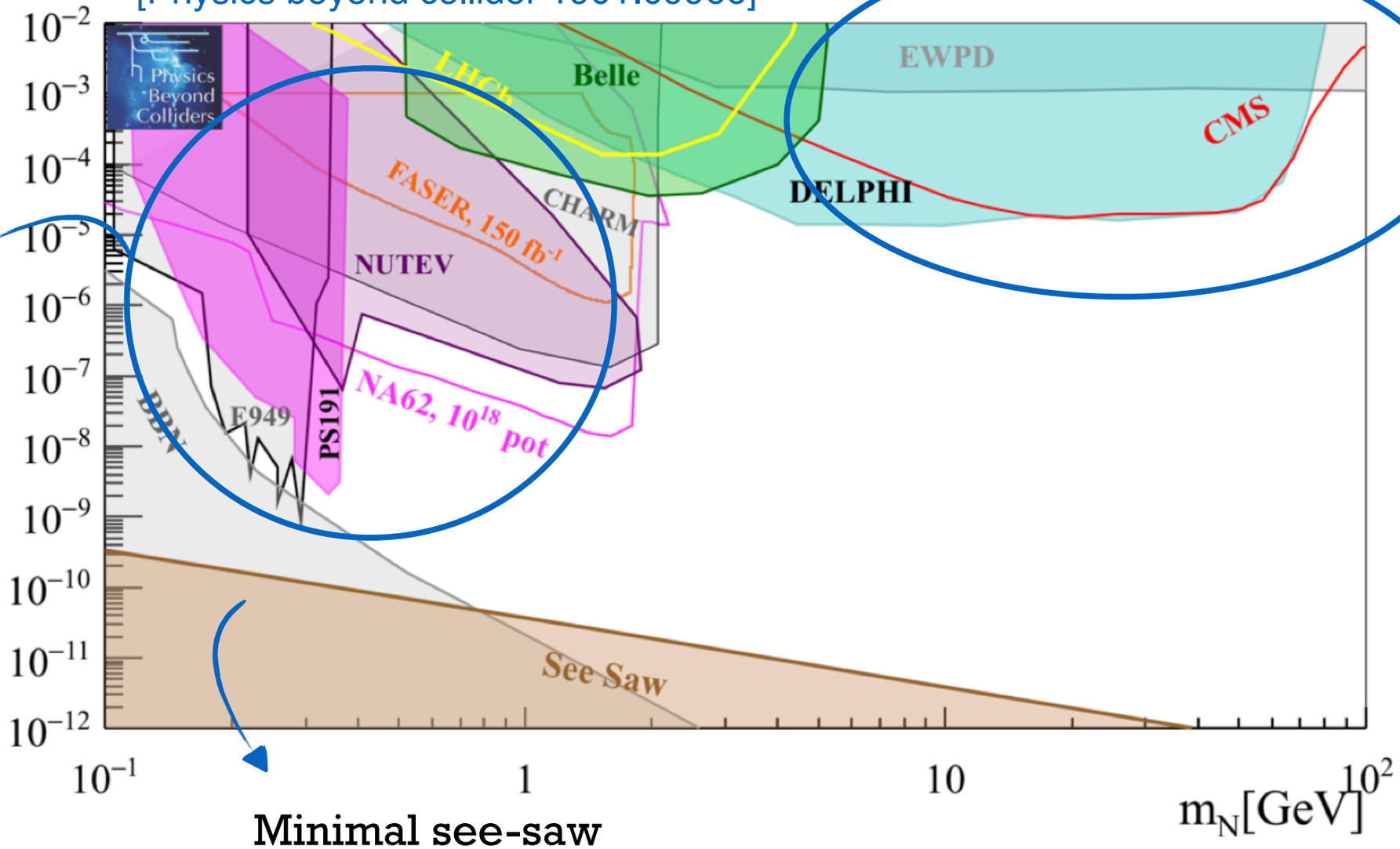
- Allow to test higher masses
- Sensitive to larger mixings

Direct production



Direct production

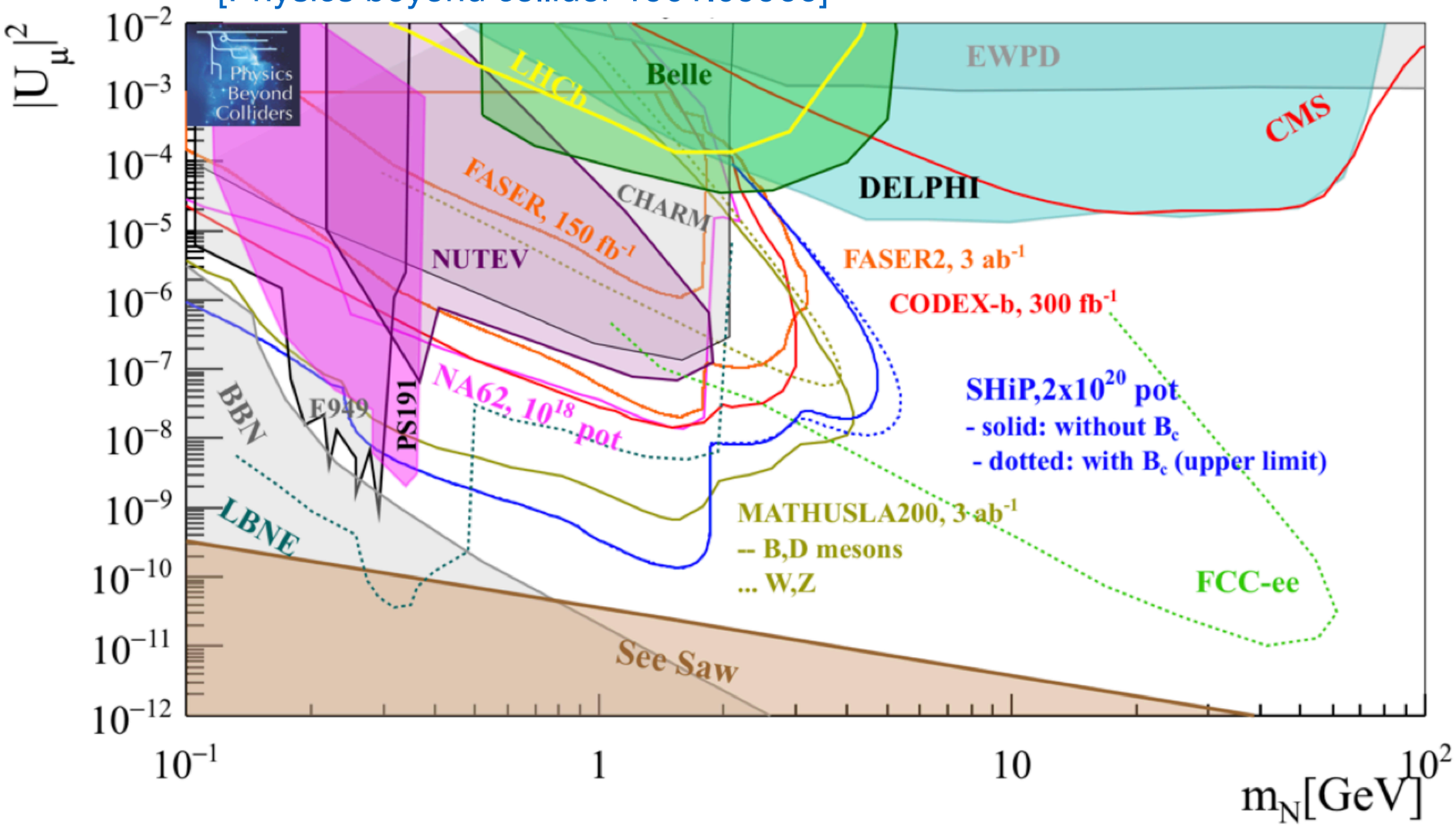
[Physics beyond collider 1901.09966]

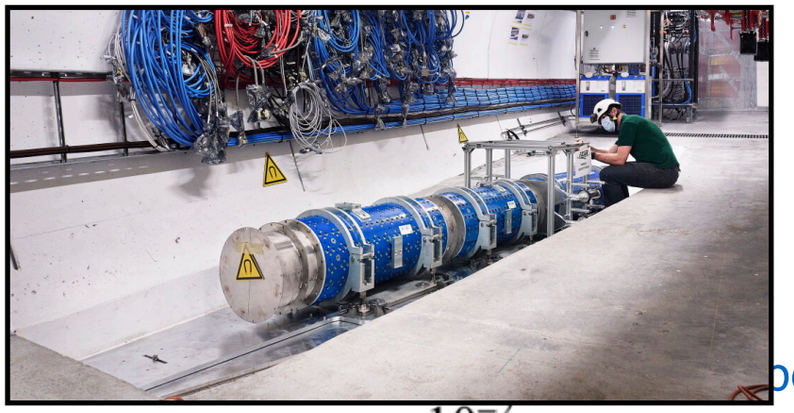


Beam-dump

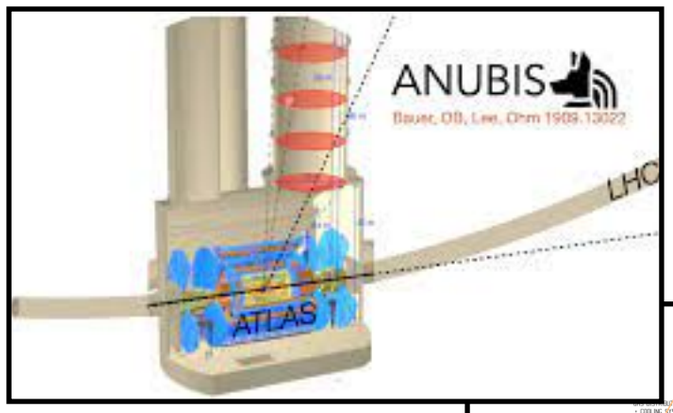
Minimal see-saw model target

[Physics beyond collider 1901.09966]

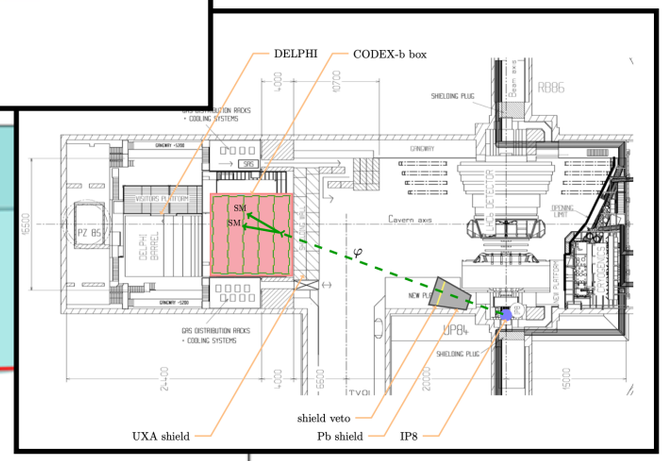


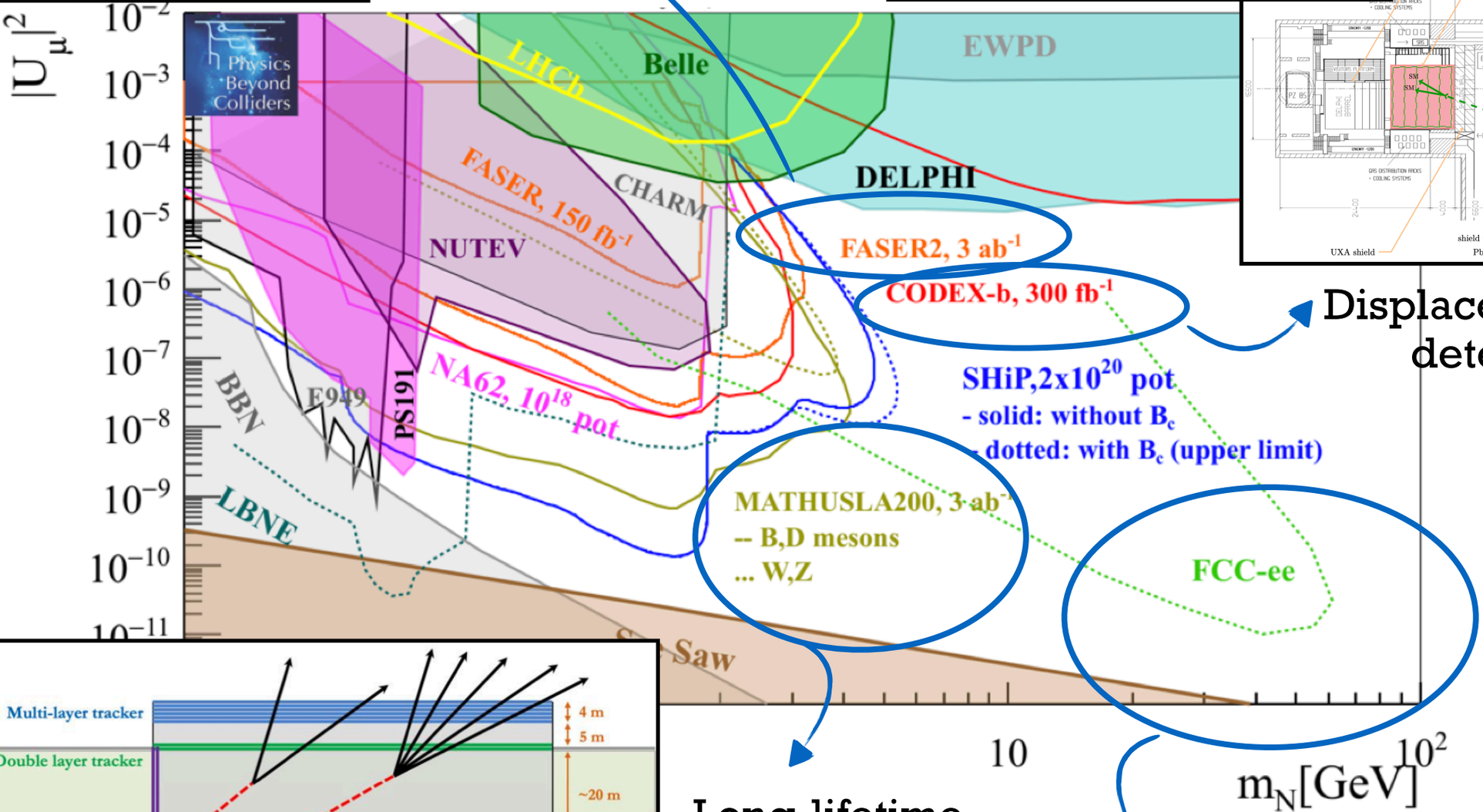


Far-forward Detectors

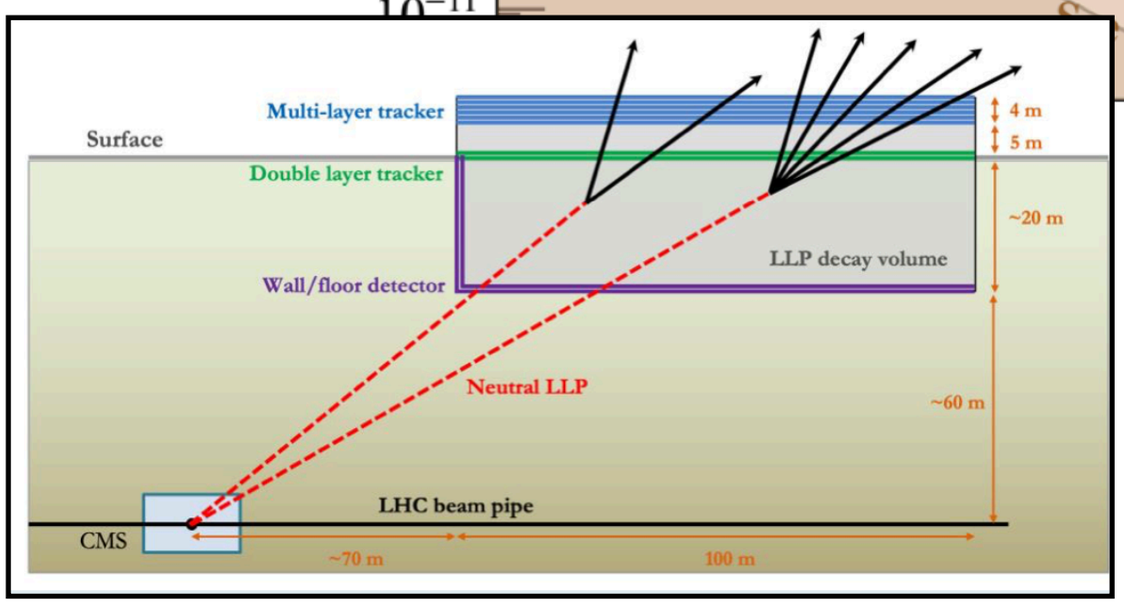


beyond collider 1901.09966]





Displaced off-axis detectors

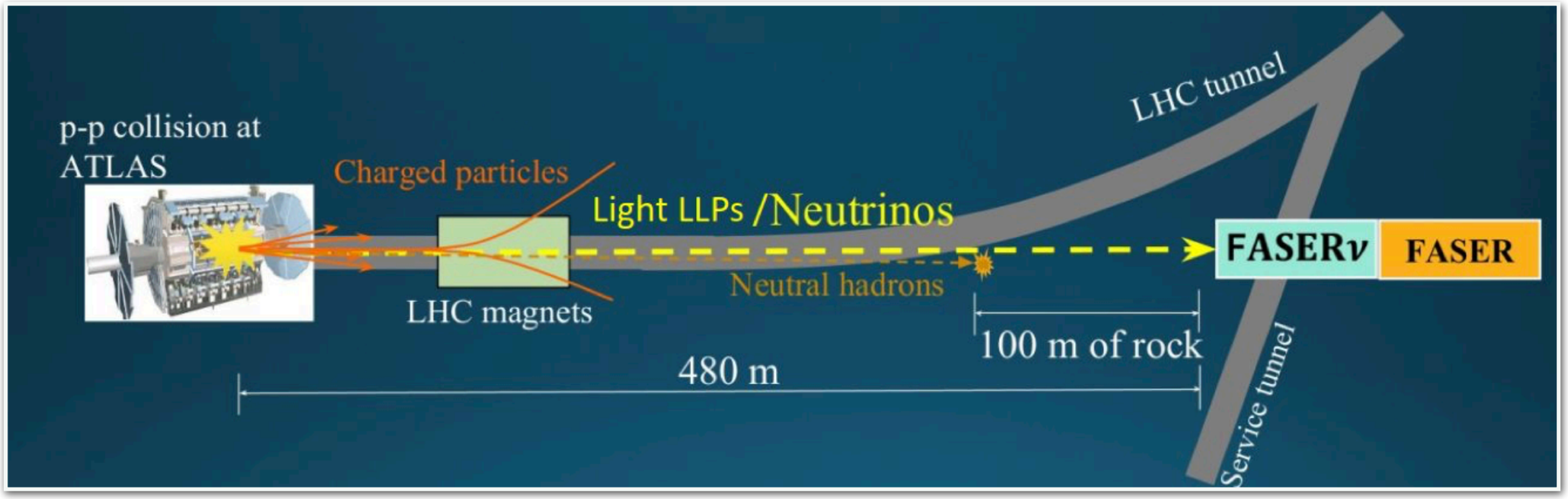


Long-lifetime Detectors

Future lepton colliders

Faser & Faser-ν experiments

- Far detector at small polar angle
- Exploit the large fluxes of forward particles produced at the LHC interaction points
- Search for LLP particles produced in vicinity of the IP point with lifetime of $\mathcal{O}(100\ \mathrm{m})$

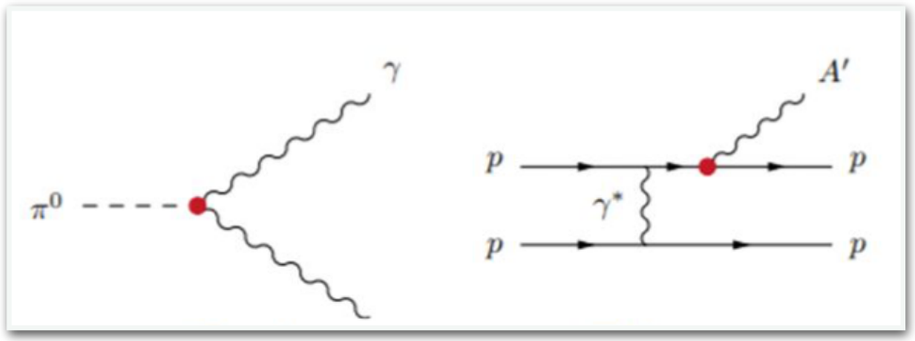


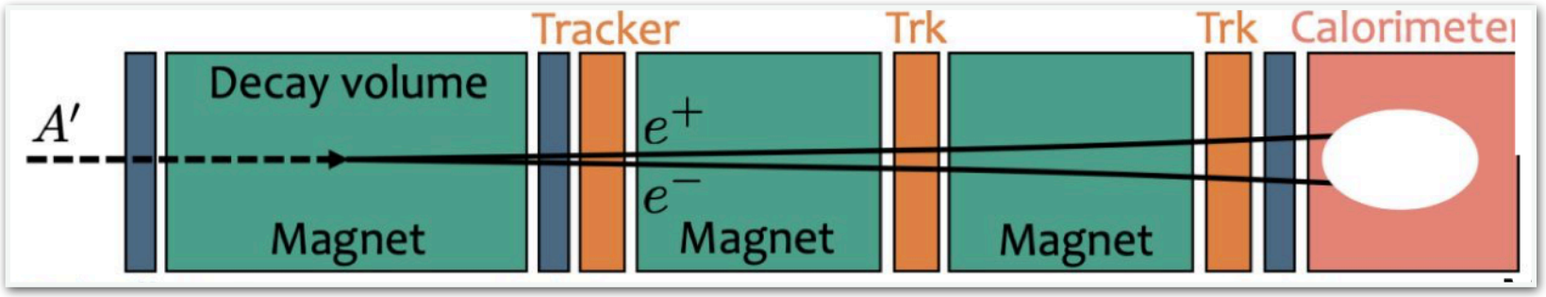
IMPORTANT - FASER IS TAKING DATA NOW!!!

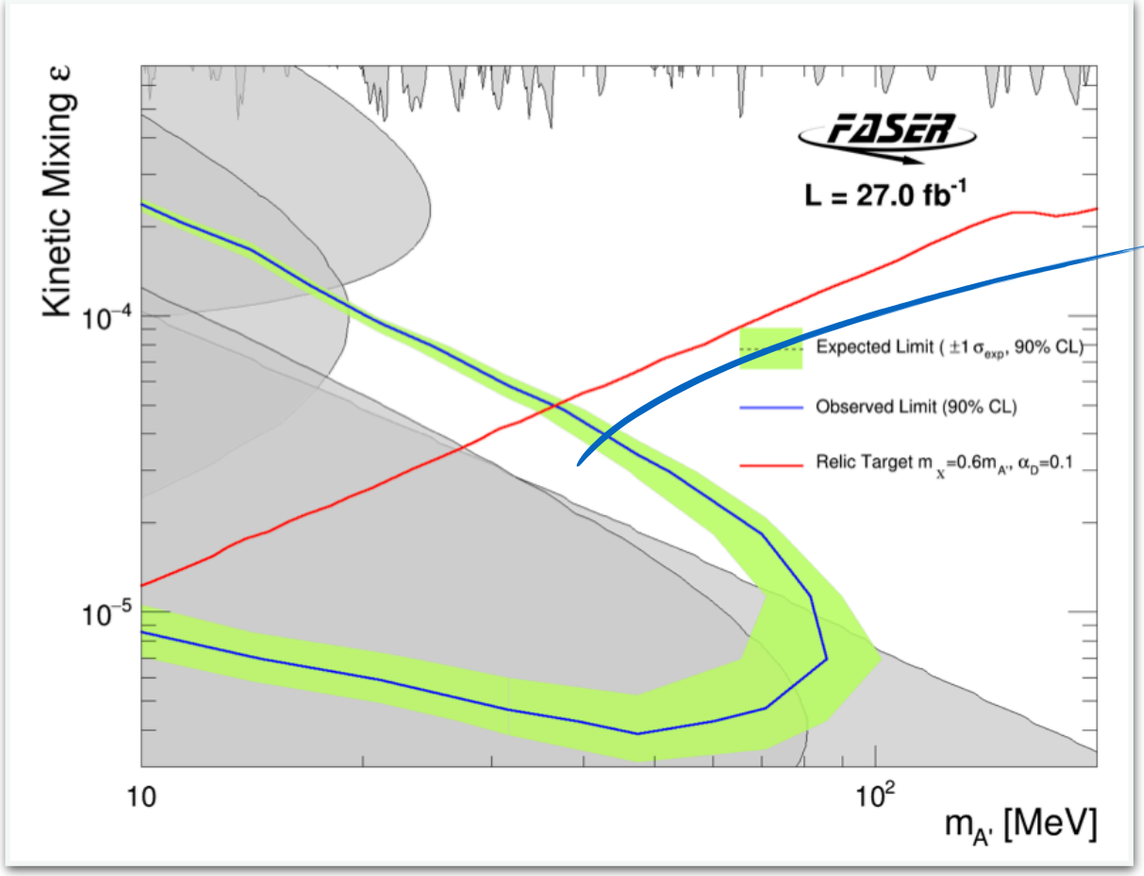
- Around $40\ \mathrm{fb}^{-1}$ of data collected at 13.6 TeV during 2022 running
- Many phenomenological studies to test different dark portal theories
- First analysis with limits on dark photons out in summer 2023

Search for Dark Photons with the FASER detector at the LHC

FASER Collaboration [FASER 2308.05587]

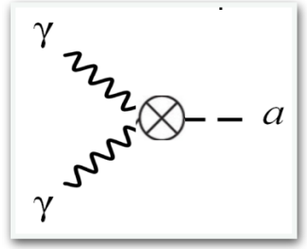






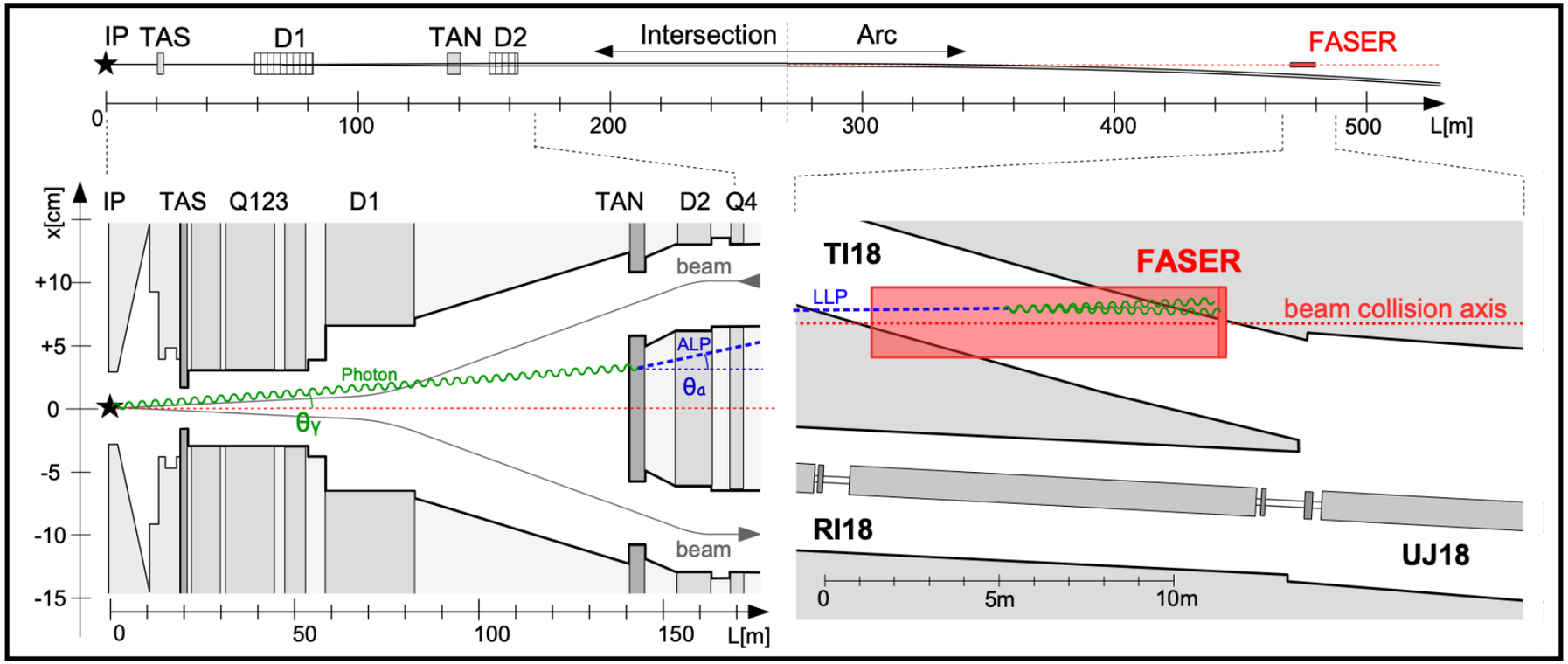
Already testing unexplored regions

- Sensitivity to ALP parameter space $\mathcal{L} \sim -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$



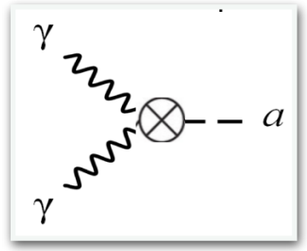
- Two main production process [Feng+ 1806.02348]
  - Direct production in $\pi^0 \to \gamma\gamma a$ rare decay at the IP
  - Primakoff process $\gamma N \to a N$ at ~ 100 m from the IP

Forward high-energy γ scatter on absorber materials and radiates a LLP ALP
Photon beam-dump



Exploits enormous forward cross-section at the LHC p p > forward ~ 100 mb

- Sensitivity to ALP parameter space $\mathcal{L} \sim -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$



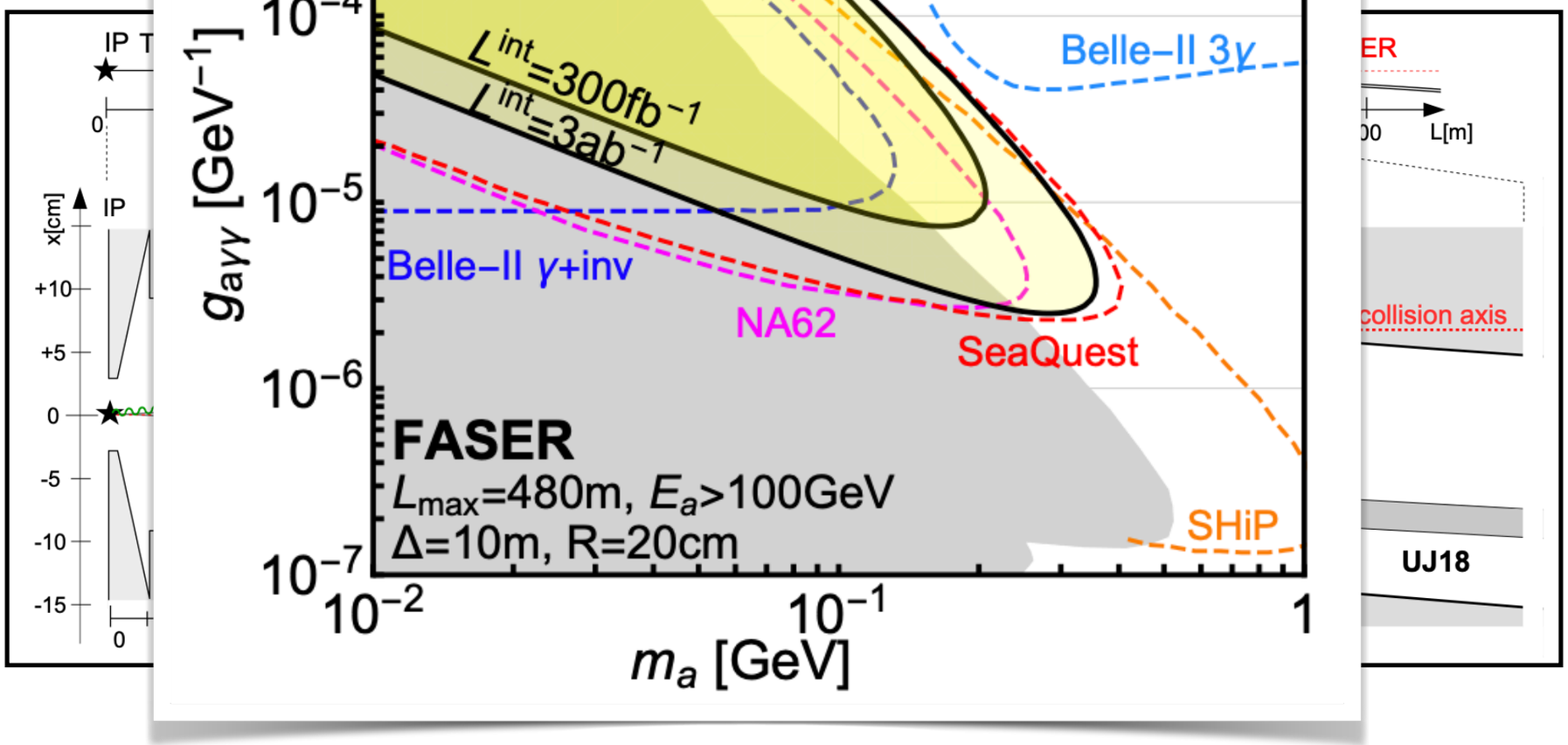
- Two main produc
[Feng+ 1806.02348]

Direct production in $\pi^0 \to \gamma\gamma a$ rare decay at the IP

~ 100 m from the IP

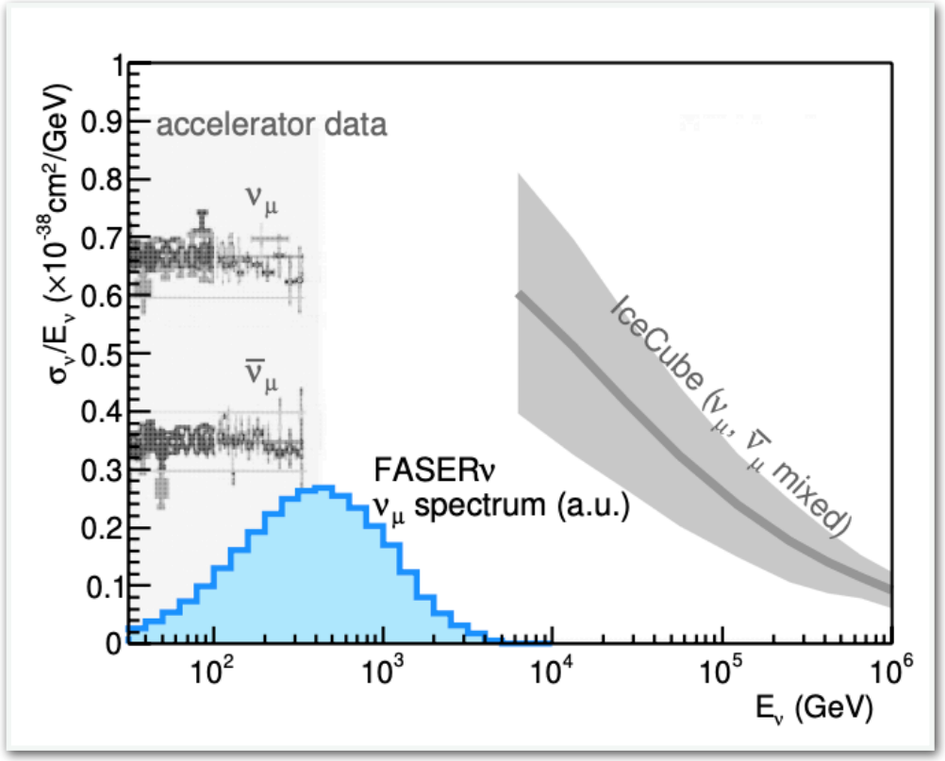
Forward hig
Photon bea

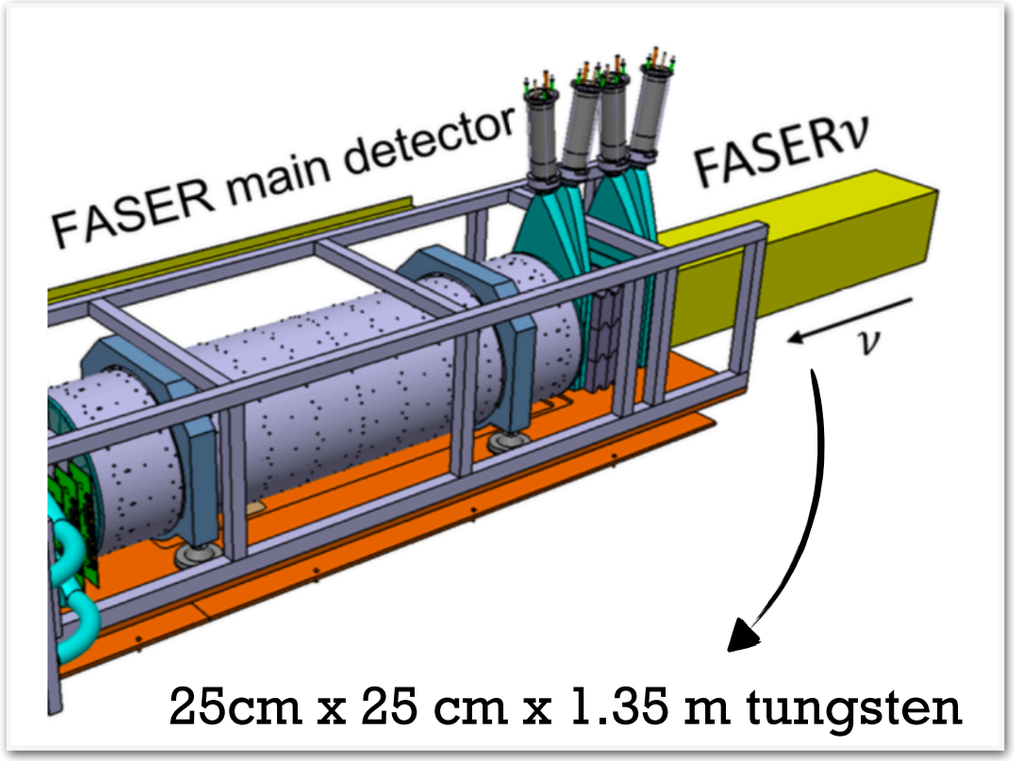
ates a LLP ALP

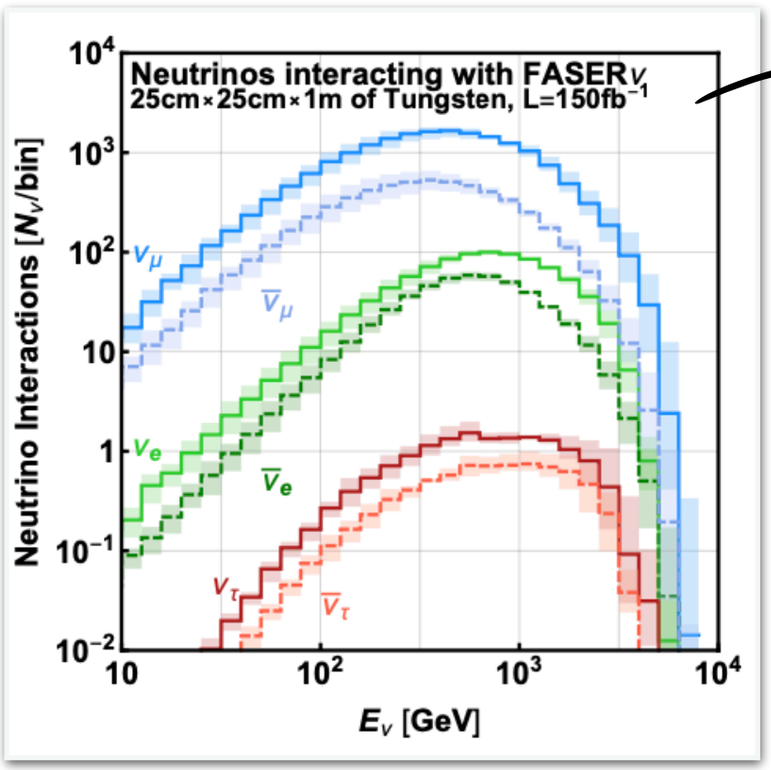


Exploits enormous forward cross-section at the LHC p p > forward ~ 100 mb

- **FASER** is also sensitive to SM neutrinos produced at the LHC, through **FASER*ν***
- Huge number of high-energy forward neutrinos from hadron decay in *pp* collisions







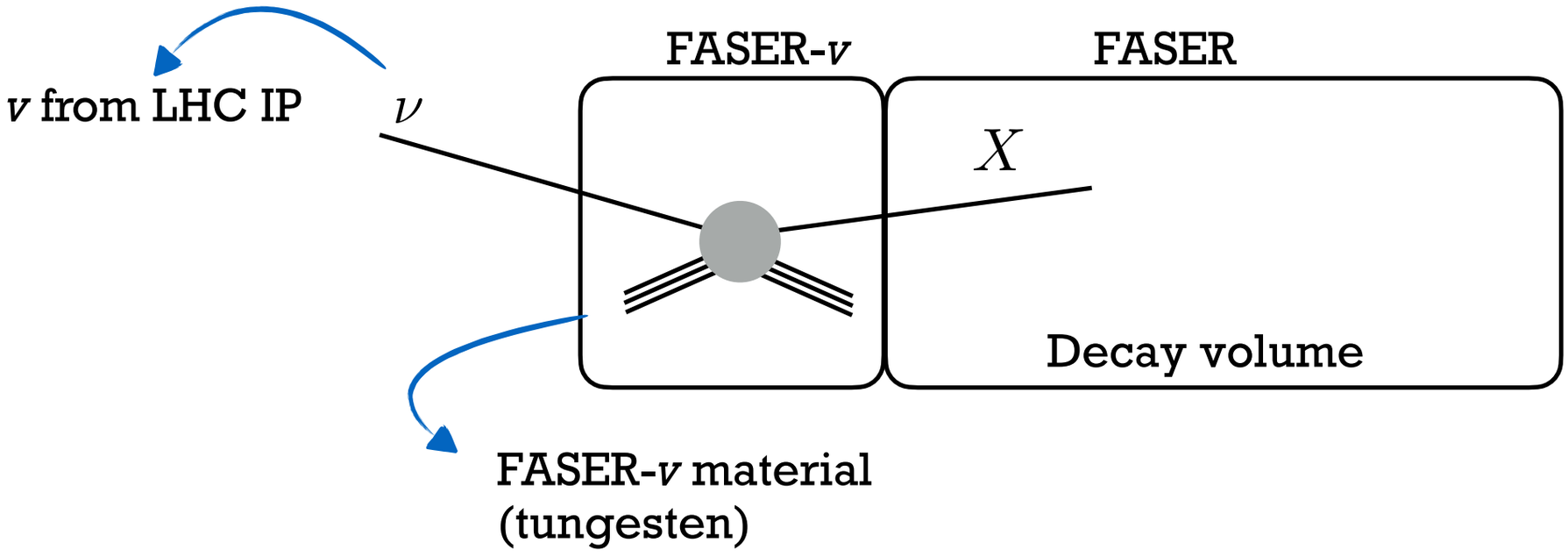
$\mathcal{O}(10^2, 10^4, 10)$ ν_e, ν_μ , ν_τ interactions

Directly test TeV neutrino properties

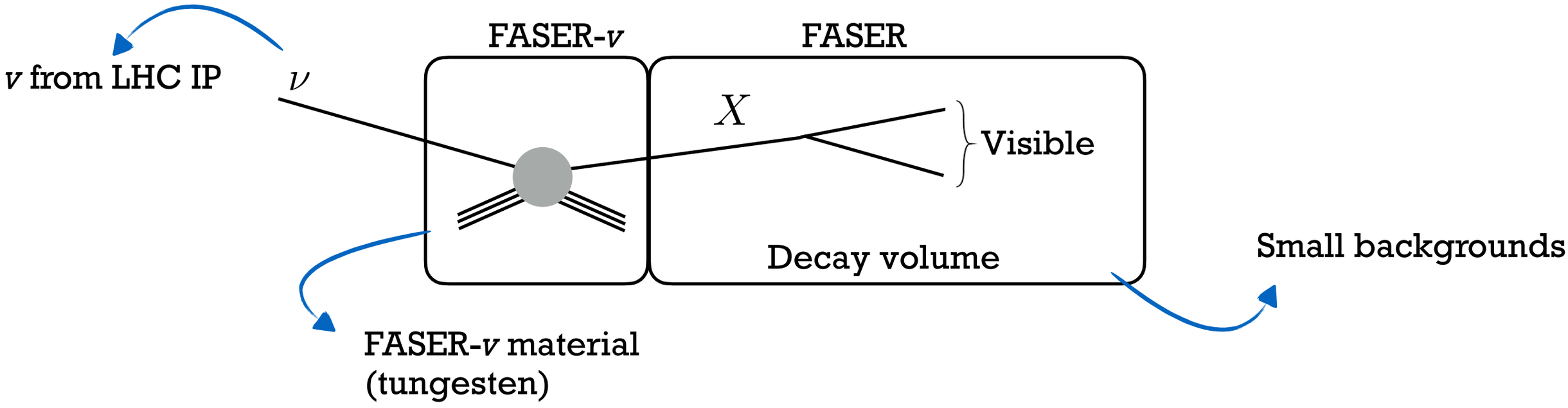
First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration [FASER 2303.14185]

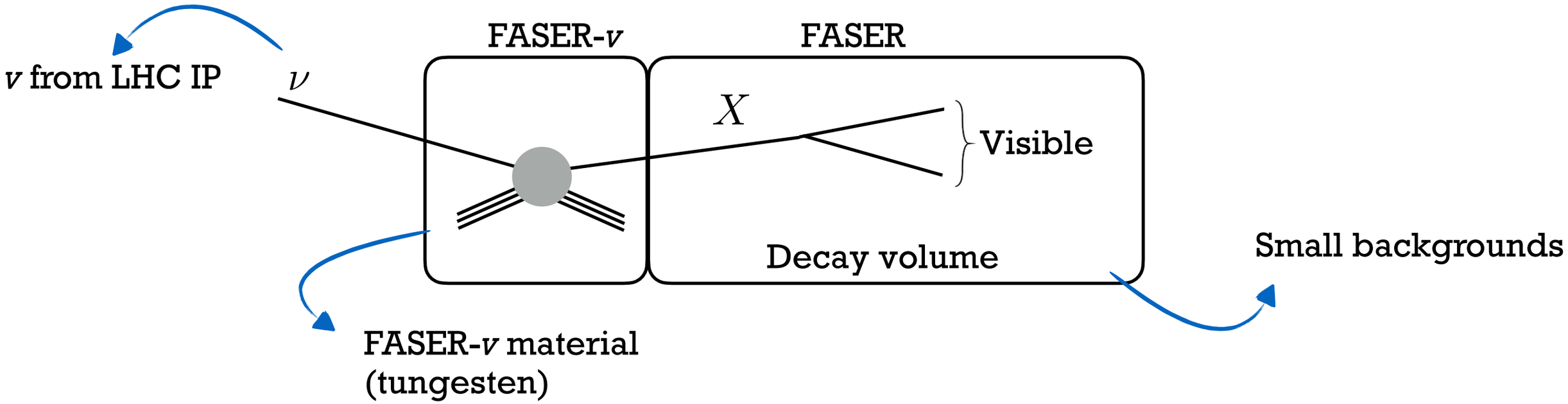
- Can also be used to test neutrino portal interaction using it as a ν beam-dump



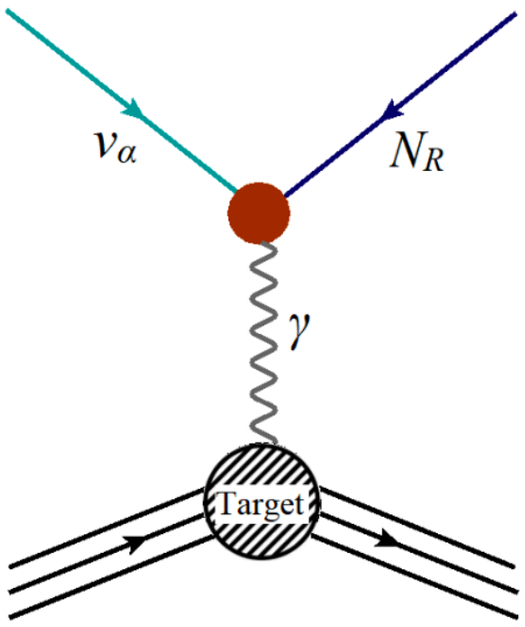
- Can also be used to test neutrino portal interaction using it as a ν beam-dump



- Can also be used to test neutrino portal interaction using it as a ν beam-dump



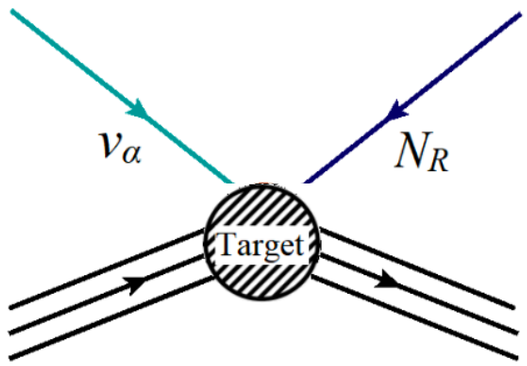
Dark dipole - $\bar{\nu}\sigma^{\mu\nu}NF_{\mu\nu}$



[Ismail+ 2109.05032]

New dark portal probes

Dark four-fermi $\bar{N}L\bar{q}u$



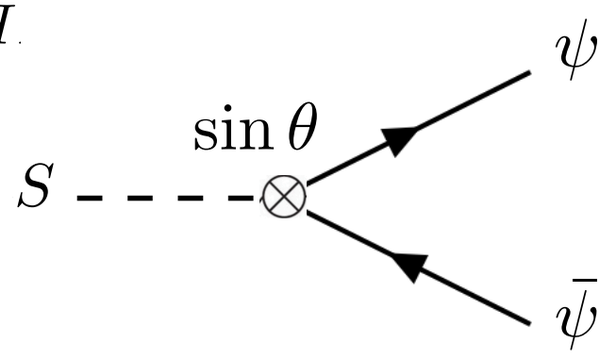
[Falkowsky+ 2105.12136] SMEFT
[DB+ 2311.xxxxx]

$$(\mu S + \lambda S^2) H^\dagger H$$

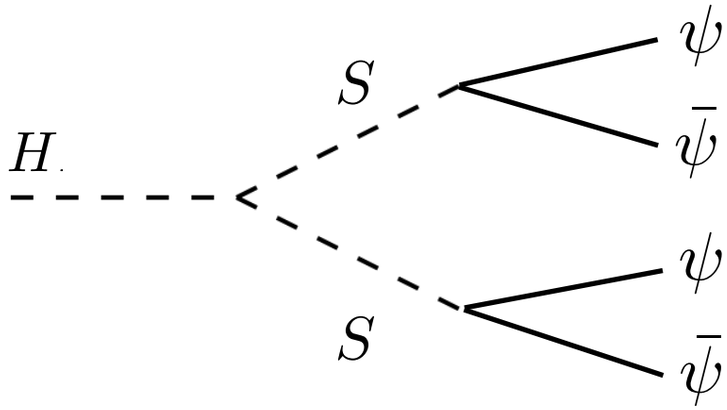
Scalar portal - the Dark Higgs

- SM Higgs mixes with the dark-Higgs

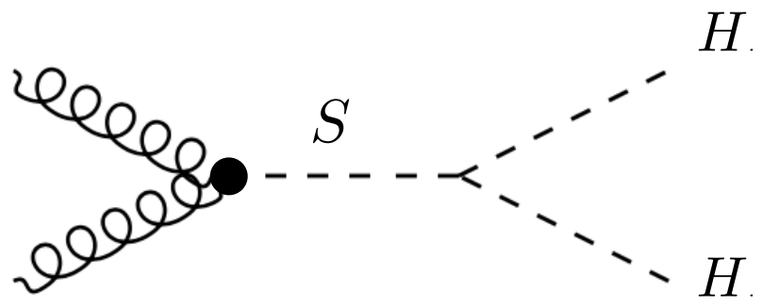
- Universal rescaling of the SM couplings



Heavy Dark Higgs - Collider searches

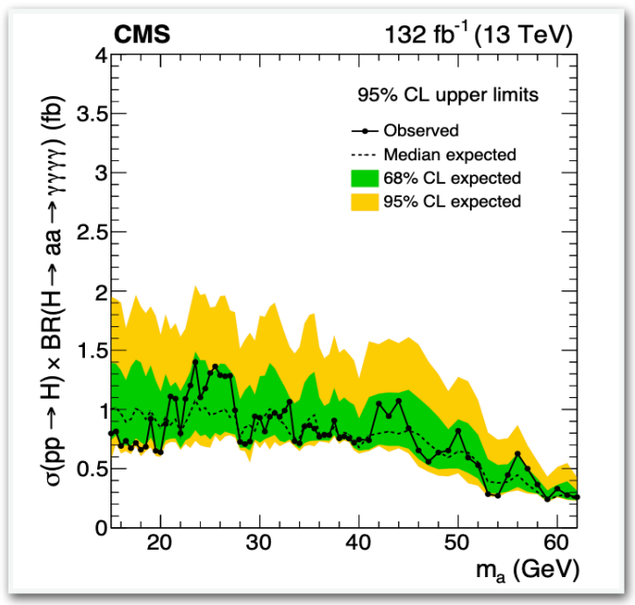


Searches for $4\mu, 4\tau, 4b, 2b2\mu \ldots$

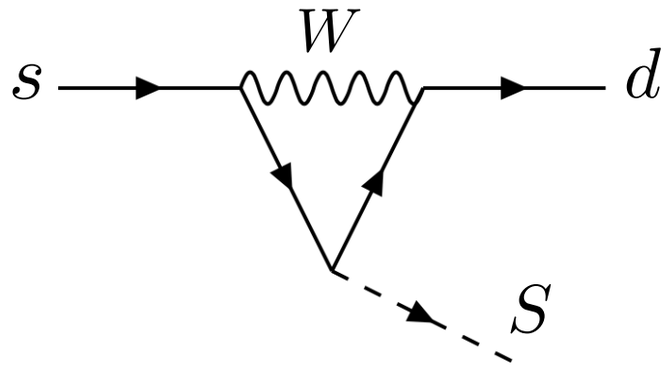


Double Higgs non resonant

Heavy Higgs searches - MSSM/NMSSM… like

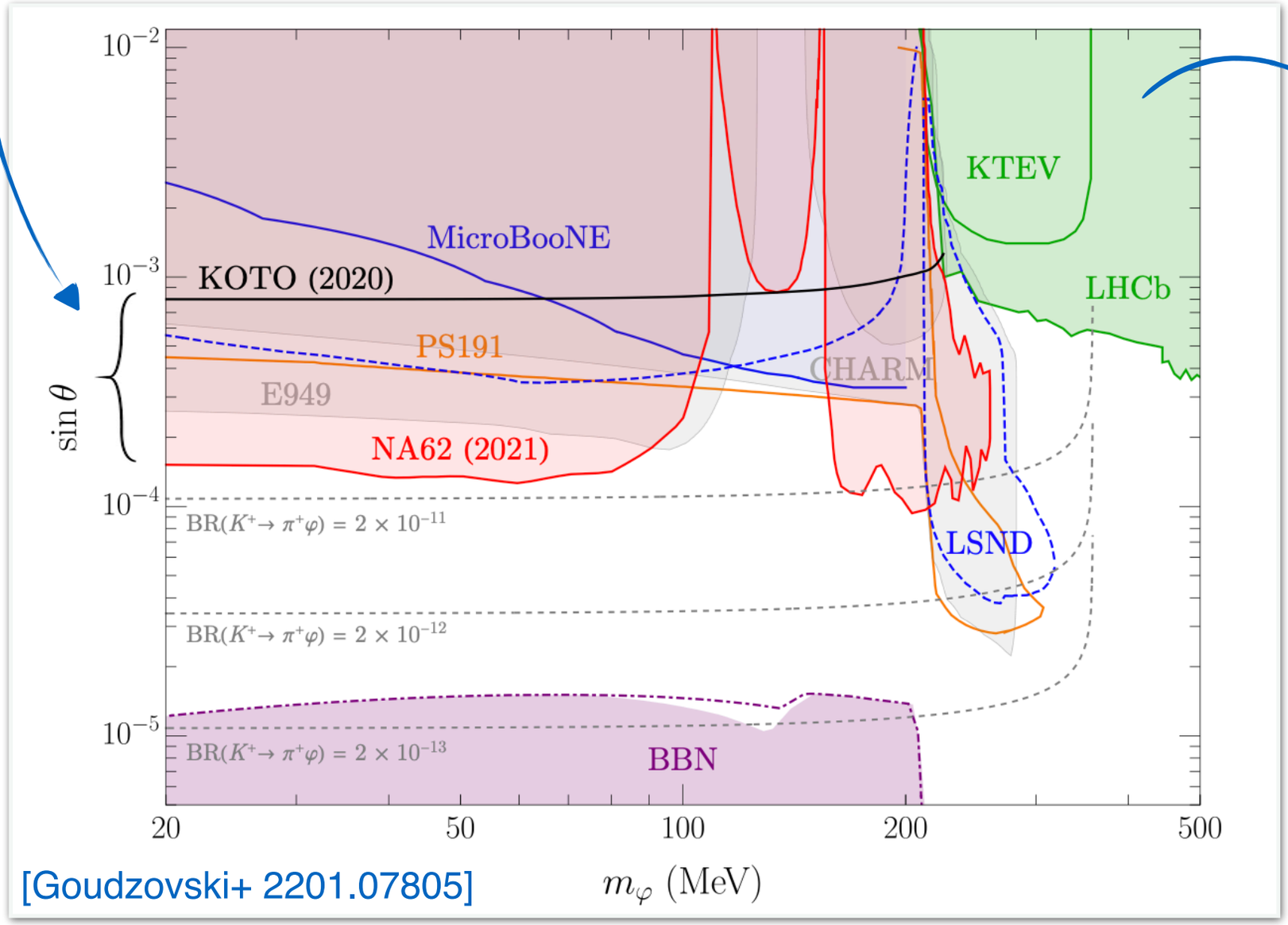


Light Dark Higgs - Beam dump & meson decay searches



Kaon factory: $K^+ \to \pi^+ S\,, \quad K_L \to \pi^0 S$

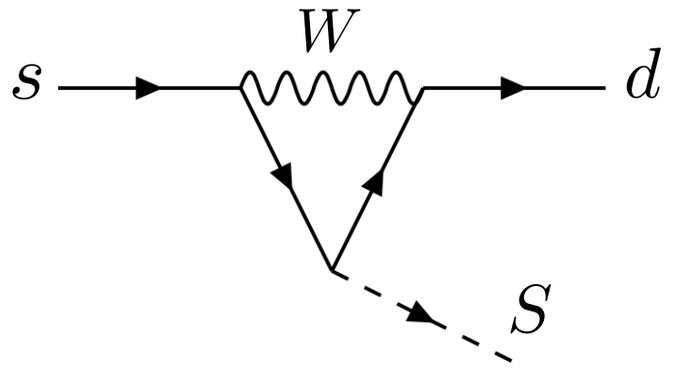
$\mathcal{B}(K^+ \to \pi^+ \varphi) = 1.7 \times 10^{-3} \sin^2\theta, \quad \mathcal{B}(K_L \to \pi^0 \varphi) = 5.7 \times 10^{-3} \sin^2\theta$



[Goudzovski+ 2201.07805]

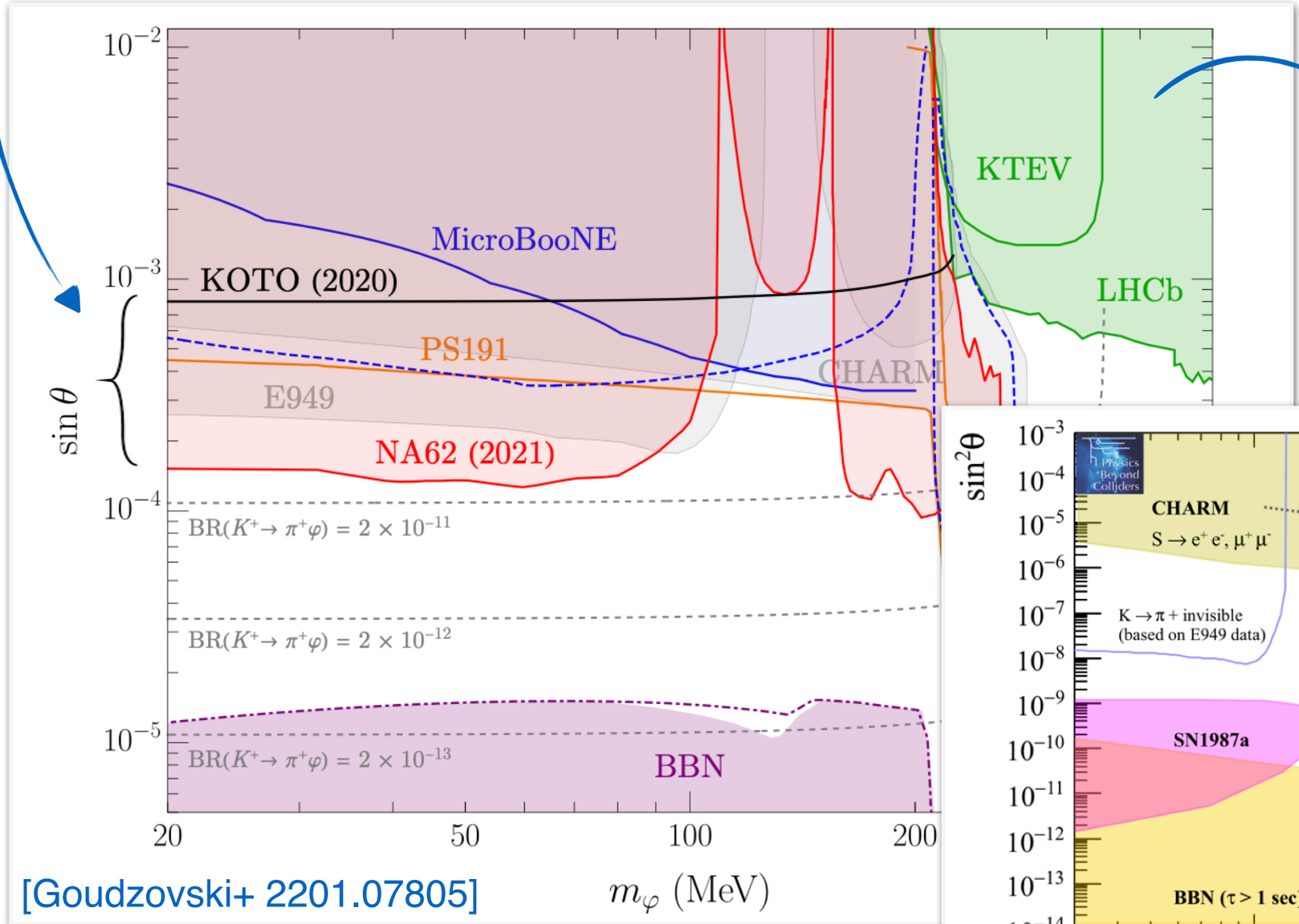
$B^+ \to K^+ S$
$B^0 \to K^0 S$
$\Big\}\ S \to \mu^+\mu^-$

Light Dark Higgs - Beam dump & meson decay searches



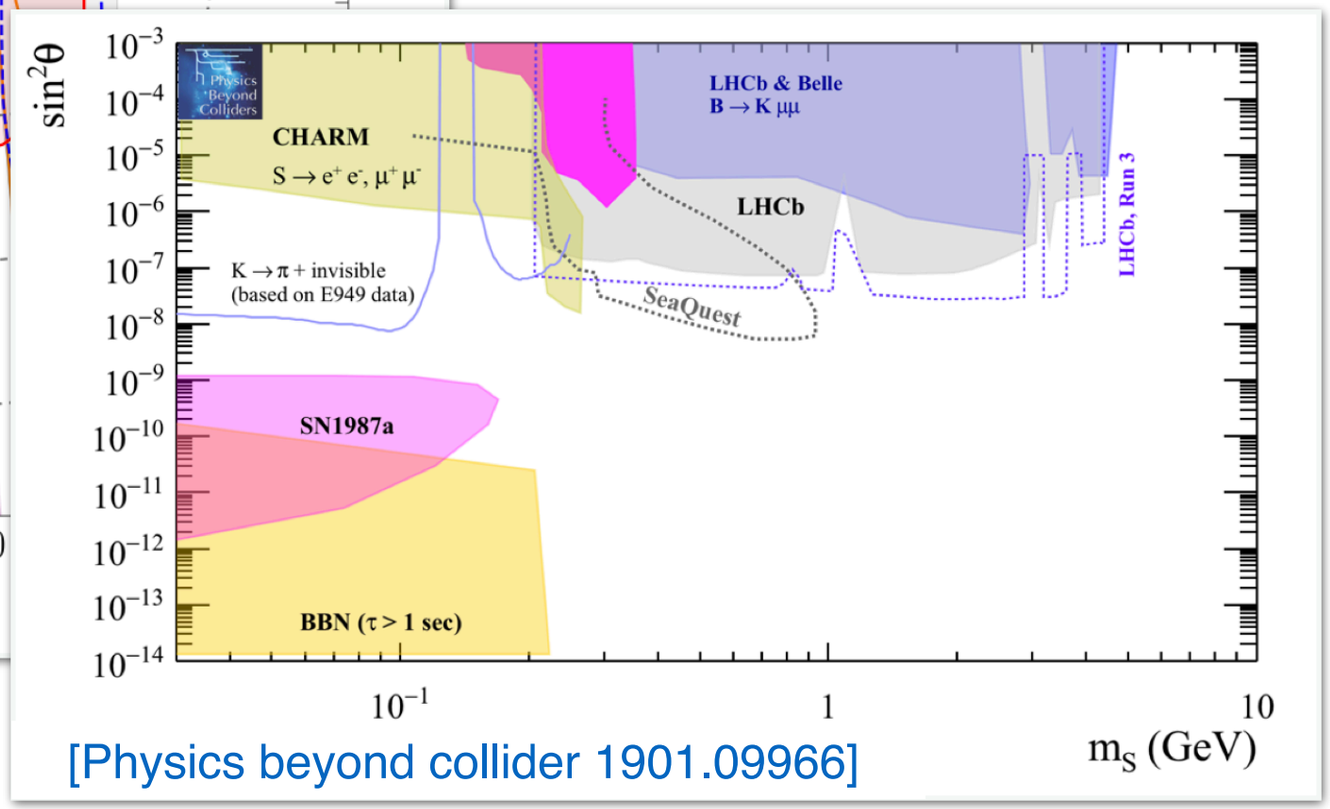
Kaon factory: $K^+ \to \pi^+ S\,, \quad K_L \to \pi^0 S$

$\mathcal{B}(K^+ \to \pi^+ \varphi) = 1.7 \times 10^{-3} \sin^2\theta, \quad \mathcal{B}(K_L \to \pi^0 \varphi) = 5.7 \times 10^{-3} \sin^2\theta$



[Goudzovski+ 2201.07805]

$B^+ \to K^+ S$
$B^0 \to K^0 S$
$\Big\}\ S \to \mu^+\mu^-$

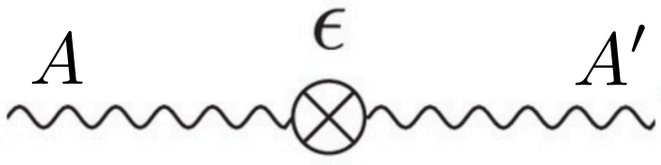


[Physics beyond collider 1901.09966]

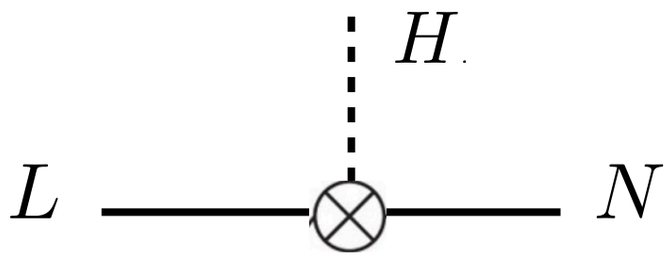
Conclusions

- Lack of signal of new physics with SM charges pushes forward the idea of dark sectors
- The minimality of renormalizable dark sector portals are well-suited to design and reinterpret experimental searches

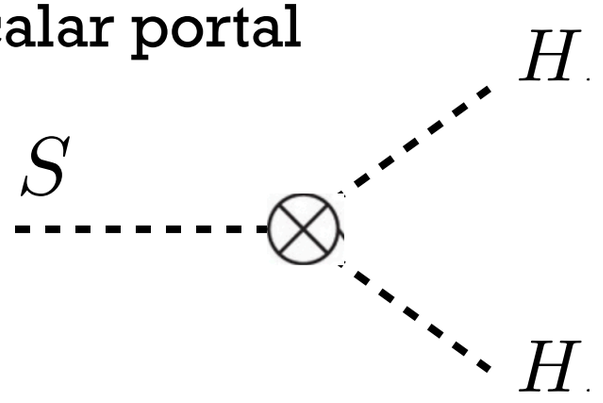
Vector portal



Fermion portal



Scalar portal



- They can be tested in a large number of low and high-energy experiments

Beam-dumps { **Classic** p, e ; **New opportunities** γ, ν → **Meson-decay**

High-energy collisions { **LHC** ; **Belle-II** ; **…**

- A large experimental program is ahead in the near future
- Use existing experiments and think about new possible signatures & experiments

Bright future ahead to illuminate dark sectors

Backup

$$\mathcal{L} = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu} + e\,J_\mu A_b^\mu + e'\,J'_\mu A_a^\mu$$

- The kinetic term can be diagonalized by a rotation

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

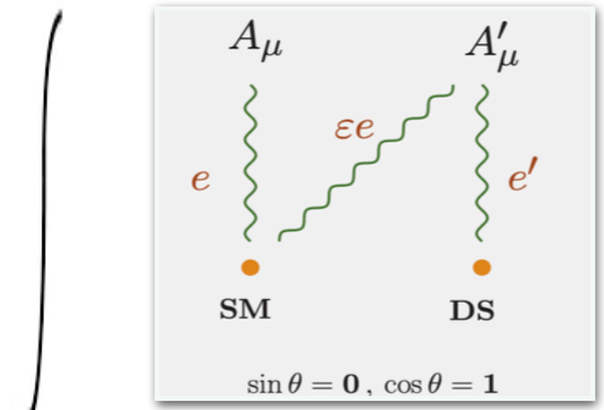
Dark photon

Photon

Arbitrary for massless DP

$$\mathcal{L}' = \left[\frac{e'\cos\theta}{\sqrt{1-\varepsilon^2}}J'_\mu + e\left(\sin\theta - \frac{\varepsilon\cos\theta}{\sqrt{1-\varepsilon^2}}\right)J_\mu\right]A'^\mu + \left[-\frac{e'\sin\theta}{\sqrt{1-\varepsilon^2}}J'_\mu + e\left(\cos\theta + \frac{\varepsilon\sin\theta}{\sqrt{1-\varepsilon^2}}\right)J_\mu\right]A^\mu$$

Two choices



$$\mathcal{L}' = \left[\frac{e'}{\sqrt{1-\varepsilon^2}}J'_\mu - \frac{e\varepsilon}{\sqrt{1-\varepsilon^2}}J_\mu\right]A'^\mu + eJ_\mu A^\mu$$

$$\mathcal{L}' = e'\,J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}}J_\mu\right]A^\mu$$

Millichage

- If there is a mass term from SSB / Stueckelberg then θ is not free anymore

$$\sin\theta = \frac{\delta\sqrt{1-\varepsilon^2}}{\sqrt{1-2\delta\varepsilon+\delta^2}} \qquad\qquad \delta = M_b/M_a$$

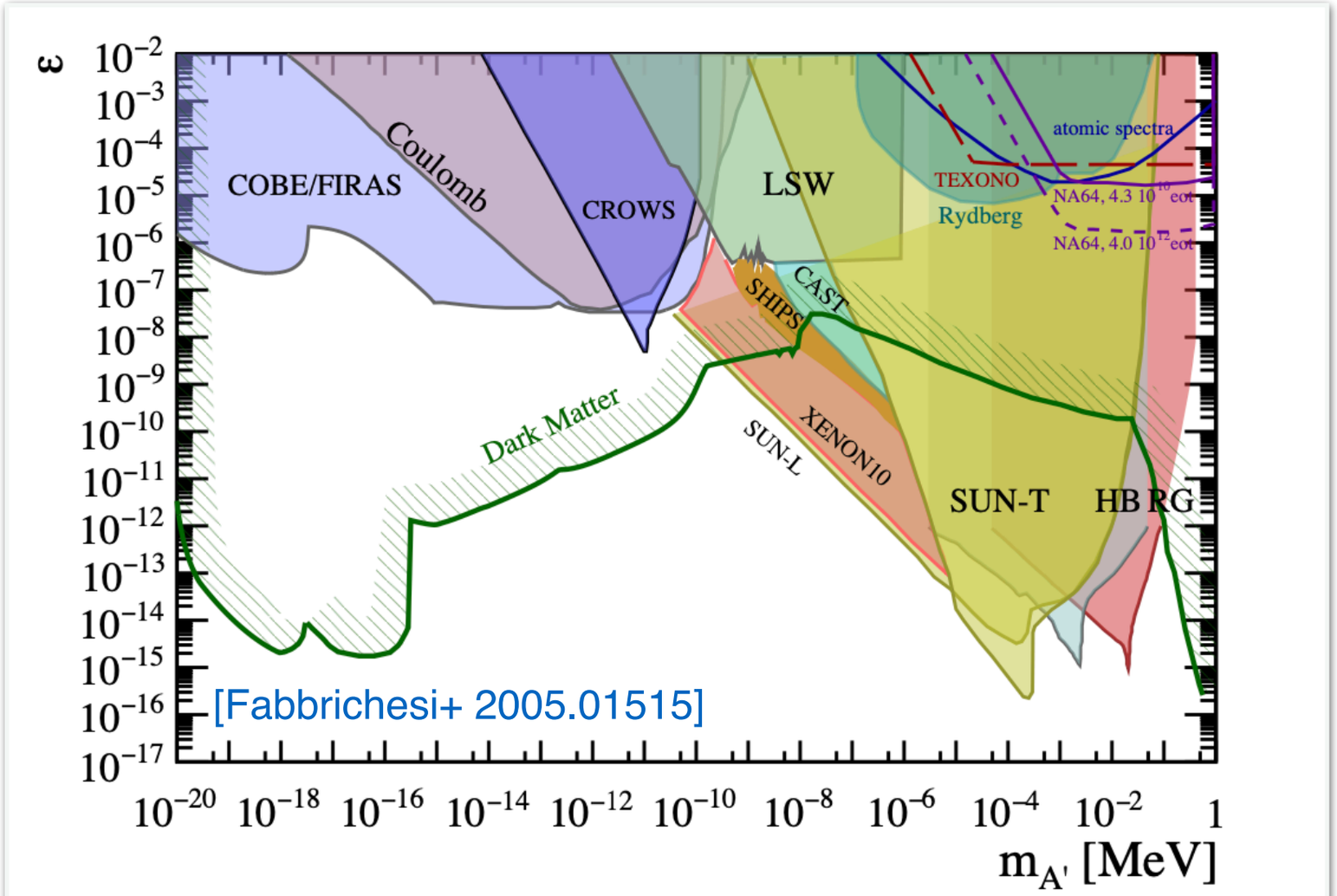
$$\begin{aligned}\mathcal{L} = & \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[\frac{e'\left(1-\delta\varepsilon\right)}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e\left(\delta-\varepsilon\right)}{\sqrt{1-\varepsilon^2}}J_\mu\right]A'^\mu \\ + & \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[eJ_\mu - \delta e' J'_\mu\right]A^\mu\,.\end{aligned}$$

- For $\delta = 0$ one obtains the “usual” dark-photon Lagrangian

$$\mathcal{L} = -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}}J_\mu A'^\mu + eJ_\mu A^\mu$$

- This is the massless limit case of the choice $\sin\theta = 0$

Dark photon below MeV



Sterile neutrino below MeV

- Modification of beta decay spectrum