A tale of two frontiers, low energy accelerators for high-energy physics.

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IP2I – CNRS

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Outline

Light particles for heavy new physics scenarios

Intensity frontier experiments and high-energy physics

GeV-scale measurement for new physics: the status of HVP and $(g-2)_\mu$

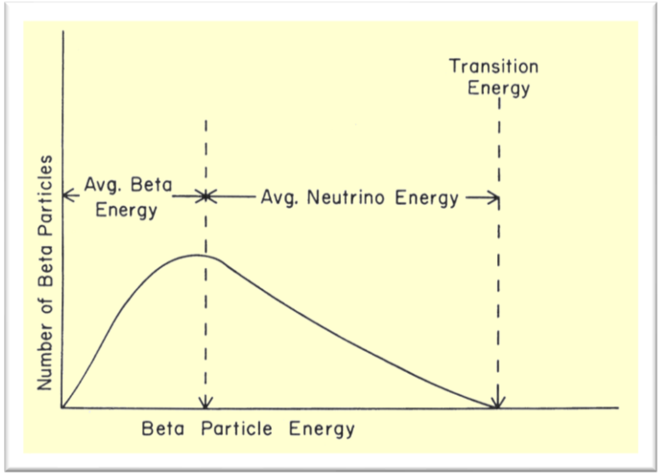
Back in time: neutrinos as a dark sector

- In the thirties, the study of beta nuclei decays led to a puzzling situation
  → Energy conservation appeared broken …

$${}^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + e^{-} + \bar{\nu}_e \quad \longrightarrow \quad {}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^{-} + \bar{\nu}_e$$

Only this part « known »!

Illustration P. Sprawls

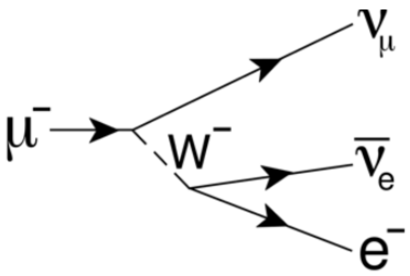


Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines […] will explain to you in more detail, how because of the "wrong" statistics of the N and Li[6] nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, […]

W. Pauli

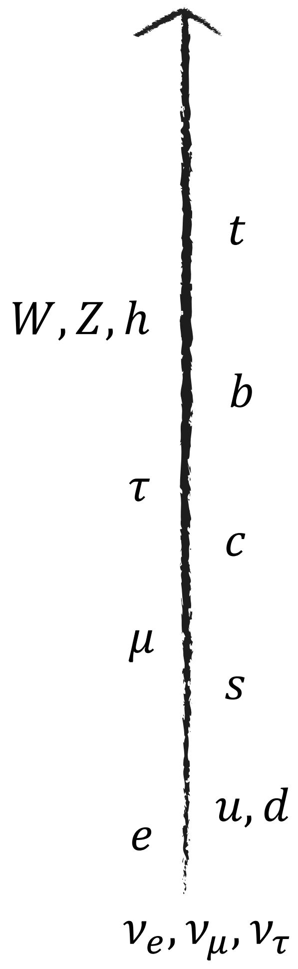
Pauli's letter of the 4th of December 1930



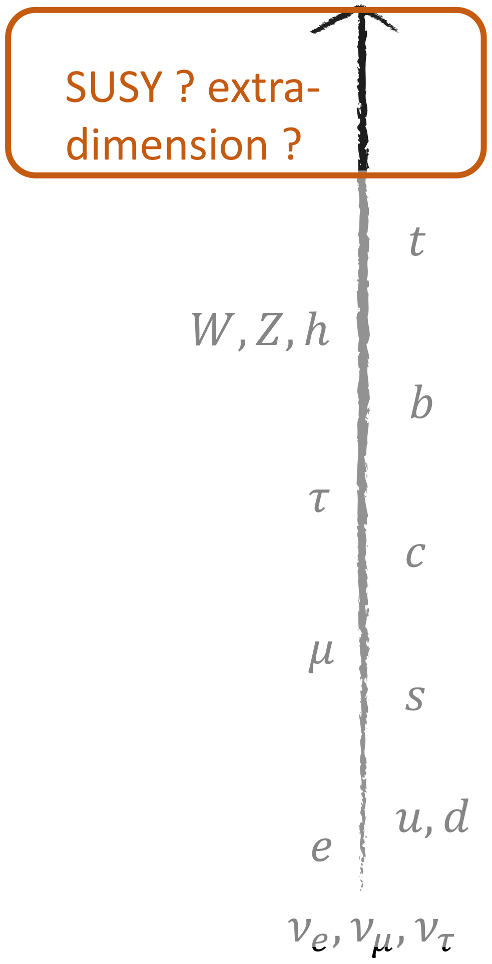
- Neutrinos where the first « dark » particles
  → Their suppressed interaction arise from UV physics: the heavy EW gauge bosons

$$\frac{g^2}{M^2} \ll G_F = 1.19 \cdot 10^{-5}\text{GeV}^{-2}$$

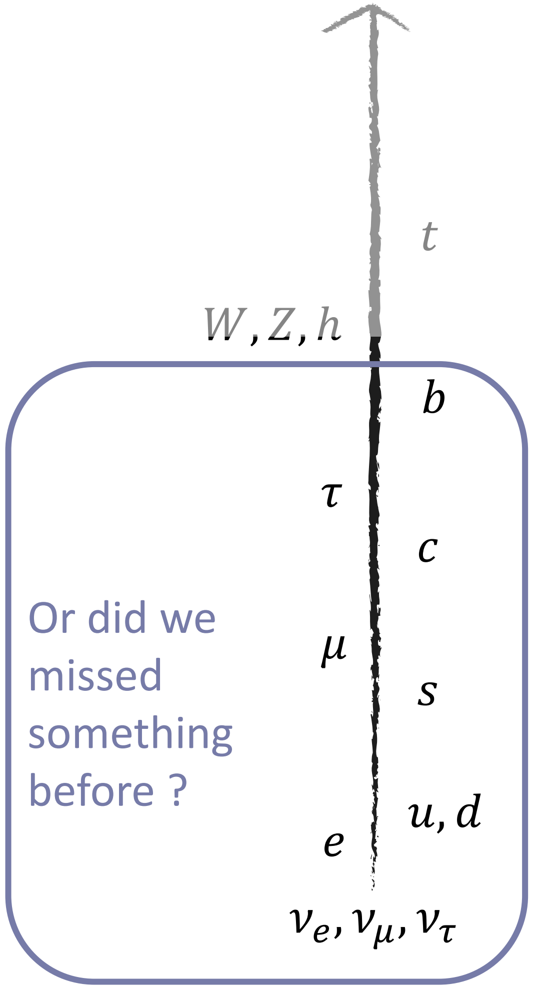
Fast forward a century: where is new physics ?



Fast forward a century: where is new physics ?



Fast forward a century: where is new physics ?



- How do you hide a light particle ?
  → *Make sure that it does not interact with the known forces …*
  → *In other word, it has to be a singlet under the gauge groups of the SM*
- Referred to as “Feebly Interacting Particle” (FIP)
  → new neutral particle which interacts with the SM via suppressed new interactions
- Key question: what would be the consequence for UV physics of the discover of a new light particle ?

Summary: portal interactions

- A simple way of parametrising FIPs interaction with the SM rely on "portal" operators

→ A neutral particle, must be coupled to a neutral "current" in the SM

	SM operator		FIPs / dark sector		
Scalar portal	$\vert H\vert^2 \quad (d=2)\,,$	$\longmapsto$	$\vert S\vert^2$	Dark Higgs	*Mixes with the standard Higgs*
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$	$F'^{\mu\nu}$	Dark photon	*Mixes with photon*
Neutrino portal	$LH \quad (d=5/2)$	$\longleftrightarrow$	N	HNL	*Mixes with neutrinos*

- New particles coupling throught these portals mostly "inherit" the properties of a SM particle at low scales

Dimension 3 portal and UV theories

- Starting from dimension 3 portal the UV theory typically has a strong impact on the structure of the low energy interactions

flavour violation, flavour non-universality, scalar vs vector operators, etc...

$$\bar{Q}_{L,i}\gamma^\mu Q_{L,j}, \bar{e}_i\gamma^\mu e_j, \ldots$$

$$V_\mu\ (\bar{Q}_{L,i}\gamma^\mu Q_{L,j}\ \ldots)$$

New gauge group, for instance $L_\mu - L_\tau, B - L\ldots$ The breaking of this gauge group introduces a new scale

$$M_V \propto g\ v_S$$

Experimentally small gauge coupling and GeV-scale particle → large VEV

$$\frac{\partial_\mu a}{\Lambda}(\bar{Q}_{L,i}\gamma^\mu Q_{L,j}\ \ldots)$$

"Axion-like particle" model: pNGB from a UV scalar sector, with mass term protected by an approximate global symmetry

$$\frac{1}{\Lambda^2}\bar{\chi}_i\gamma^\mu\chi_j(\bar{Q}_{L,i}\gamma^\mu Q_{L,j}\ \ldots)$$

Fermi-like theories: generic for all new UV theories with a light dark fermionic sector.

Intensity frontier experiments and high-energy physics

An example: B-L gauge boson

- Given the SM fermionic content: can we add a new gauge interactions ?
  → Main constraints are from gauge anomalies
  → No flavour-universal solution but hypercharge
  → Given right-handed neutrinos, so-called B-L gauge group is anomaly-free

Also widely used in GUT scenarios, LR-symmetric constructions, etc…

- Based on two SM global symmetries (as protected as possible), the gauge boson interacts with all SM particles, with charges given by

$$q_u = q_d = \cdots = \frac{1}{3} \text{ and } q_e = q_{\nu_e} = \cdots = -1$$

- We add a simple Higgs sector to break this symmetry

$$\mathcal{L}_V = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + (D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4 \longrightarrow \begin{cases} M_V \propto g_{B-L}\, v_S \\ M_S \propto \sqrt{2\lambda_S}\, v_S \end{cases}$$

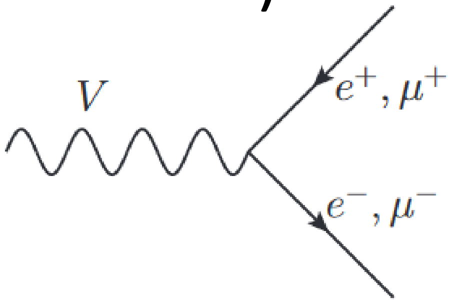
Probing FIPs in the lab: colliders

Most limits are extracted using the DarkCast code

- Search for prompt decay in pp colliders forward region (for a narrow resonance)

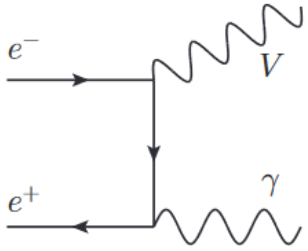
LHCb, CMS …

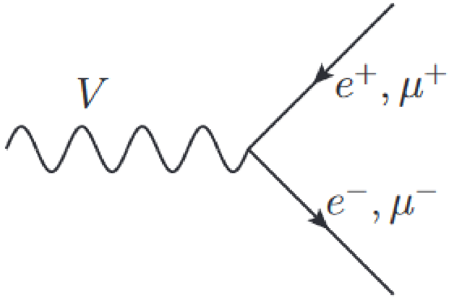
FASER, CODEX-b, MATHUSLA …

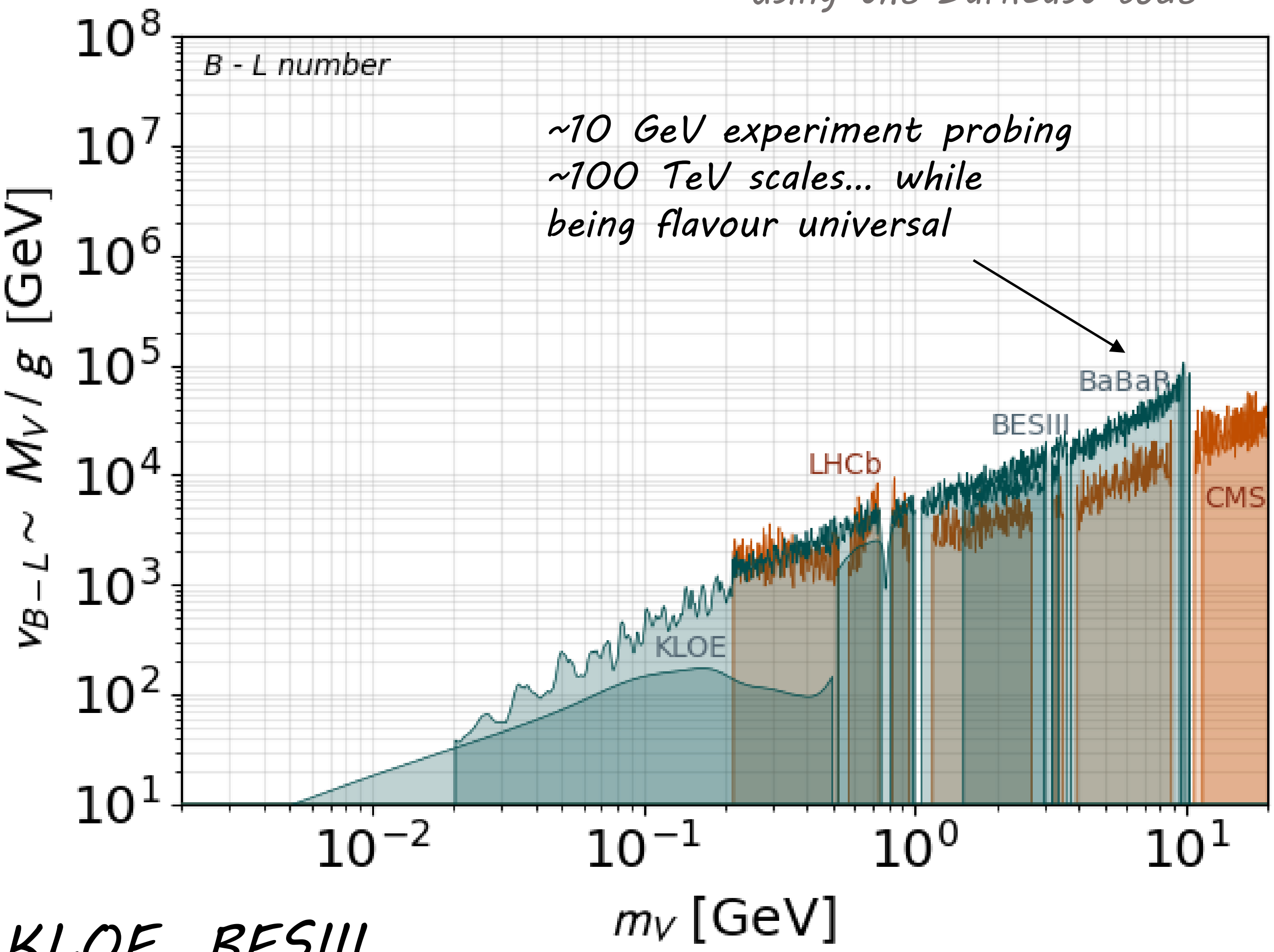


- In ee collider, in association with a γ

  → In e^+e^- and $\mu\mu$ final states





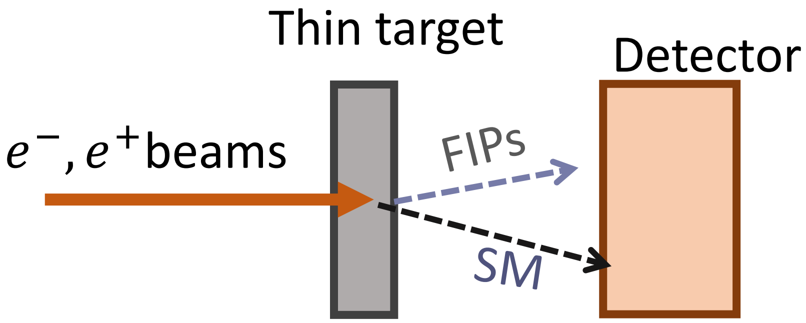


KLOE, BESIII, BaBaR, BELLE-II …

Probing FIPs in the lab: fixed targets and mesons

- Fixed (thin) target experiment

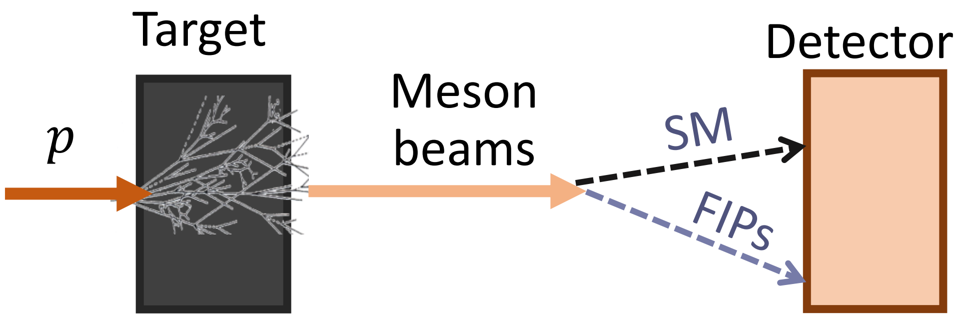
  → Lower CoM energy but higher intensity

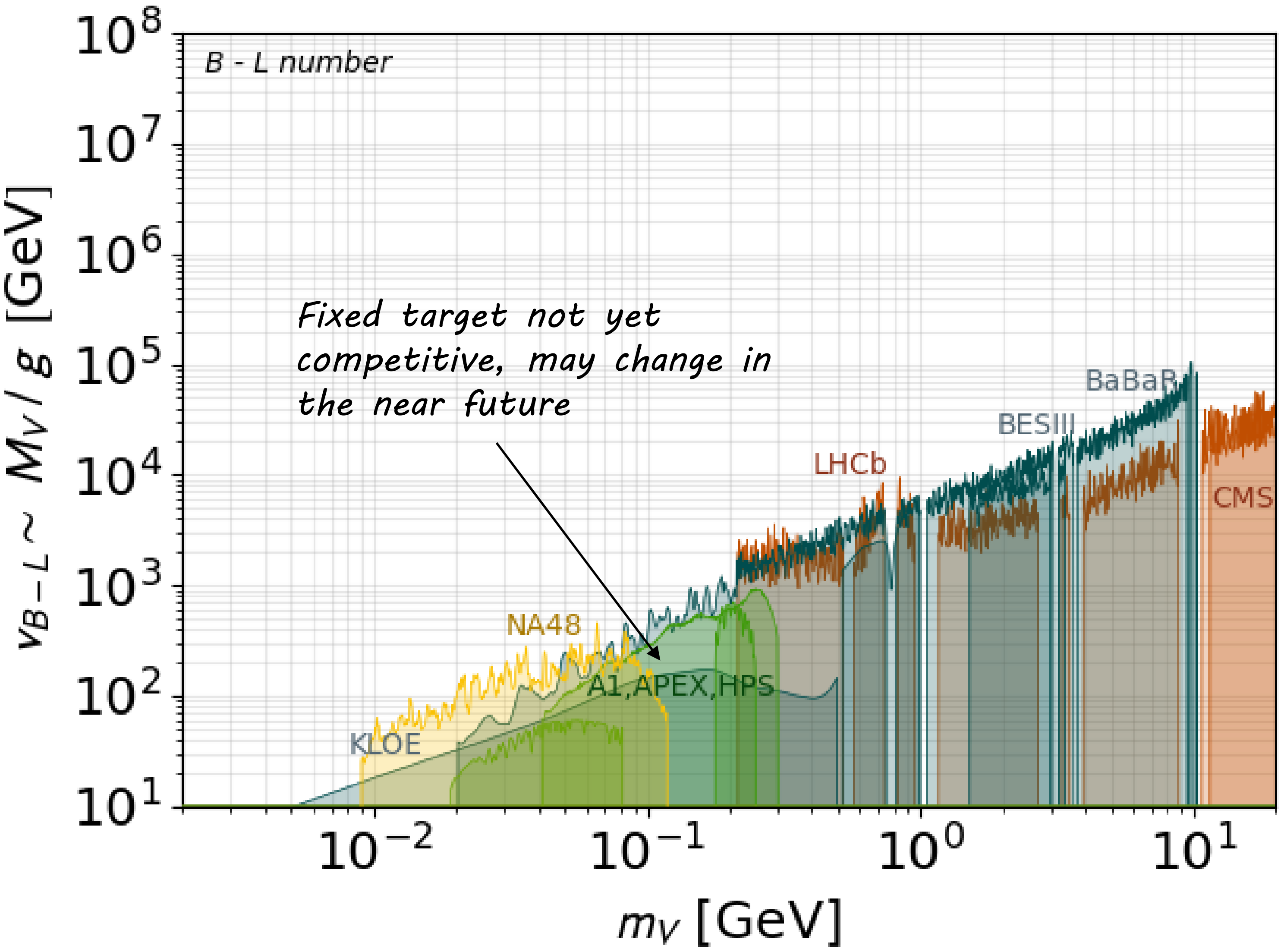


PADME, MMAPS,HPS, BDX, DARKMESA

- Mesons factories

  → $\pi^0 \rightarrow V\gamma$, flavour-violating decays

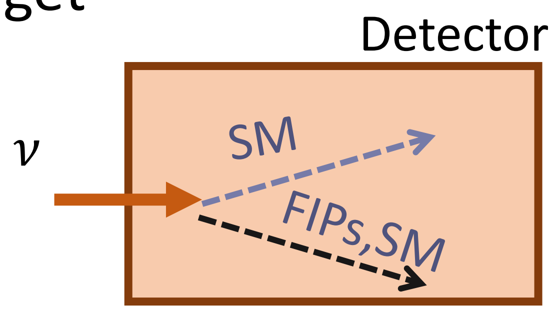




Neutrino experiments

- Neutrino experiments provides a « neutrino » beam in their near detector

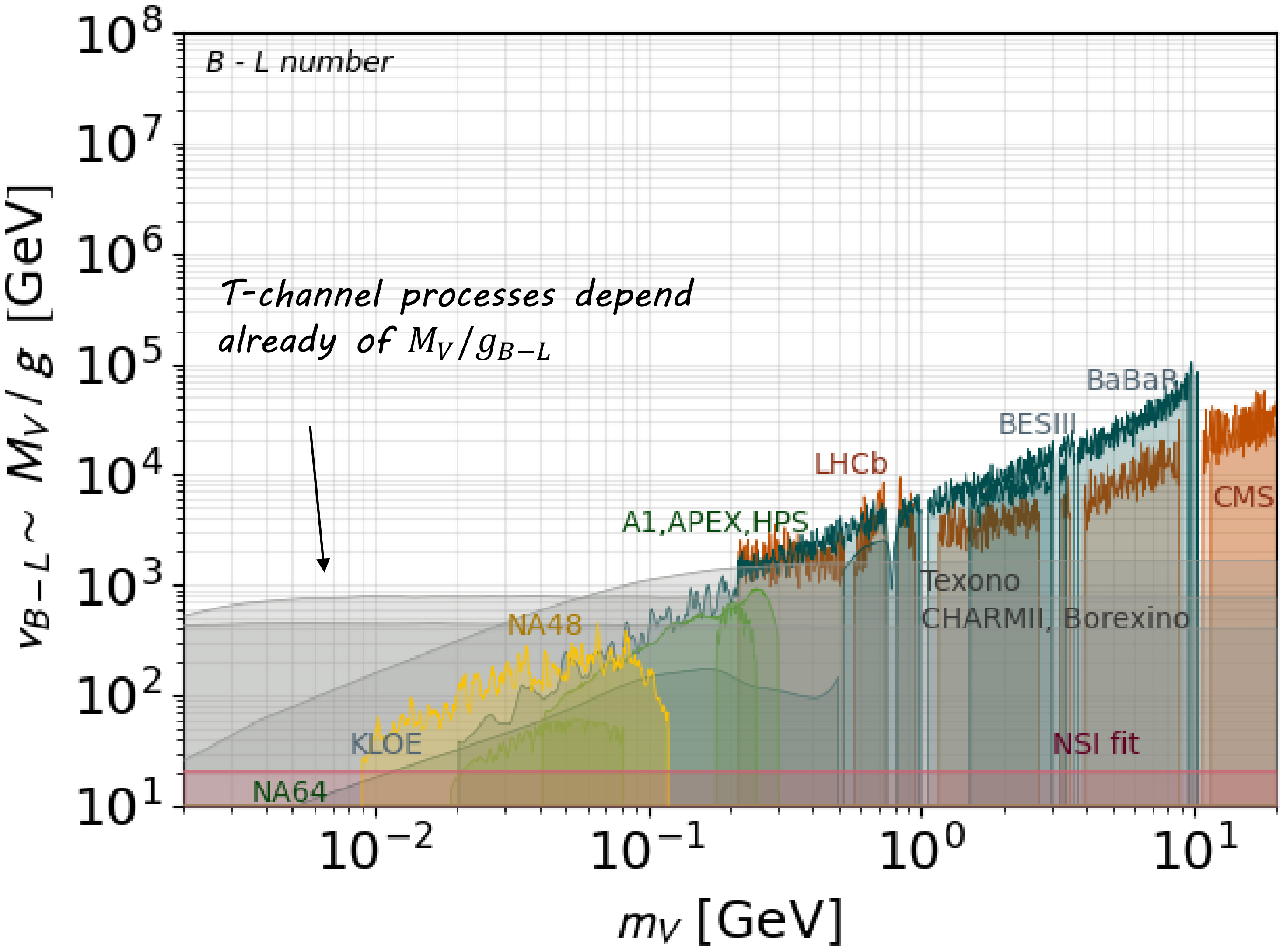
  → The detector acts as an active target



- Current constraints are from t-channel / trident production

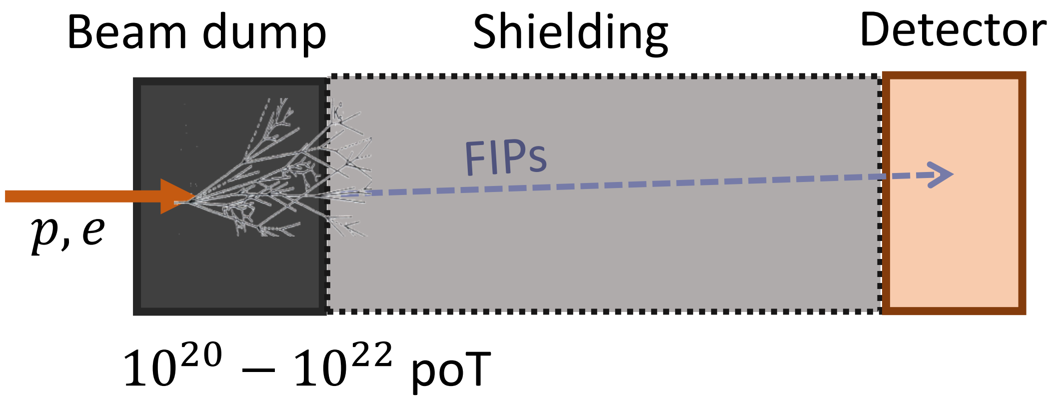
TEXONO, Borexino, CCFR

DUNE, etc…

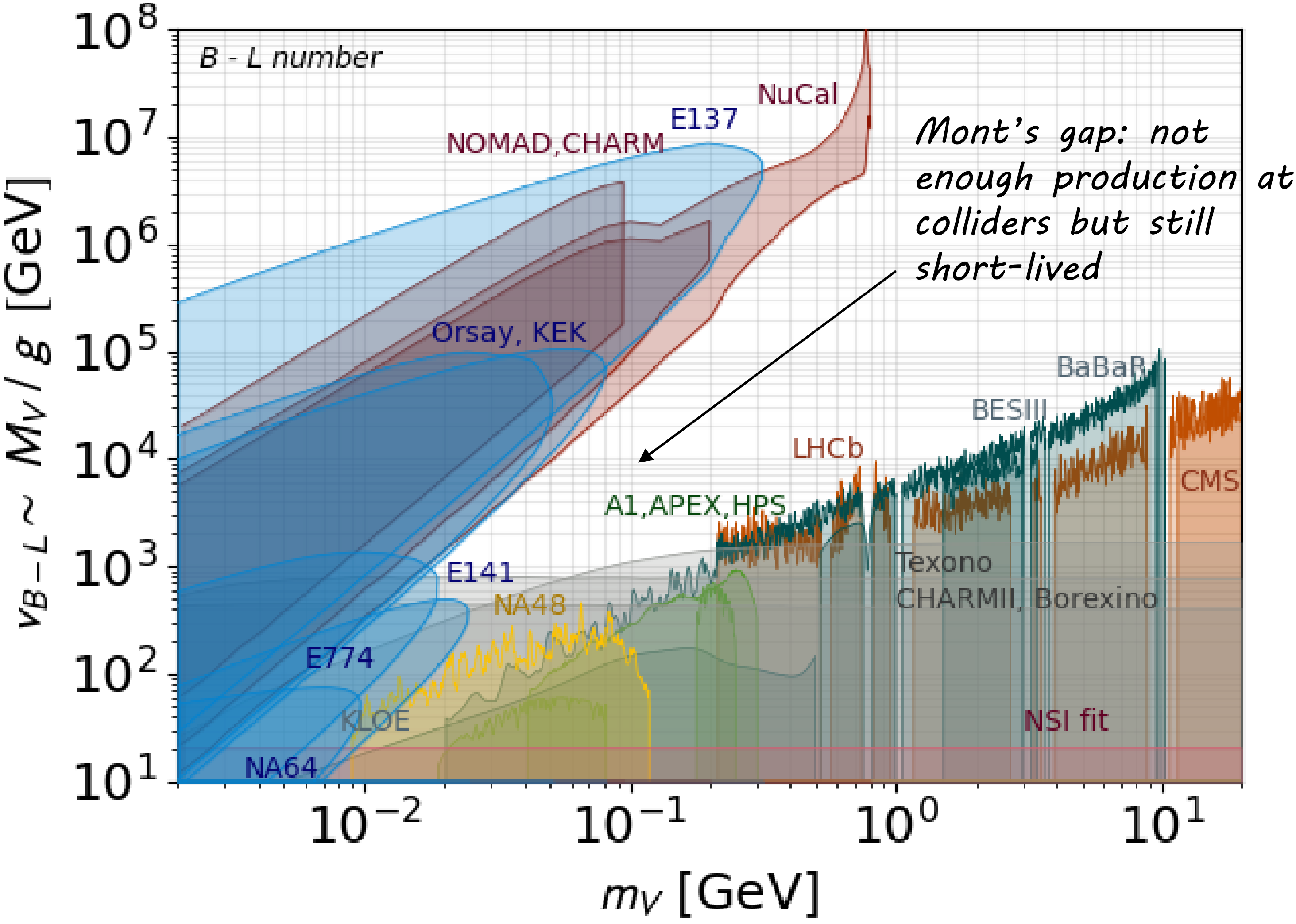


Probing FIPs in the lab: p and e beam dumps

- Numerous FIP production mechanisms
- Requires a visible signal !
  - → Displaced FIP decay
  - → FIPs or DM re-scattering

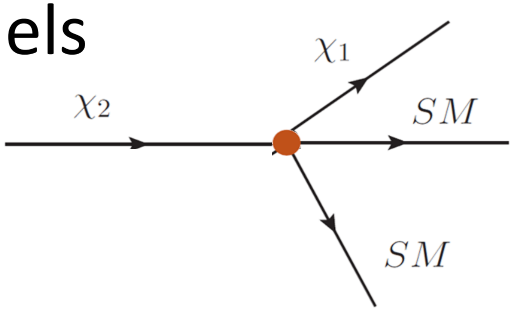


SBN program, SeaQuest, T2K, NA64, SHIP, DUNE…



Serendipity of dark sector searches …

Use a four-fermion operators derived from inelastic dark matter models

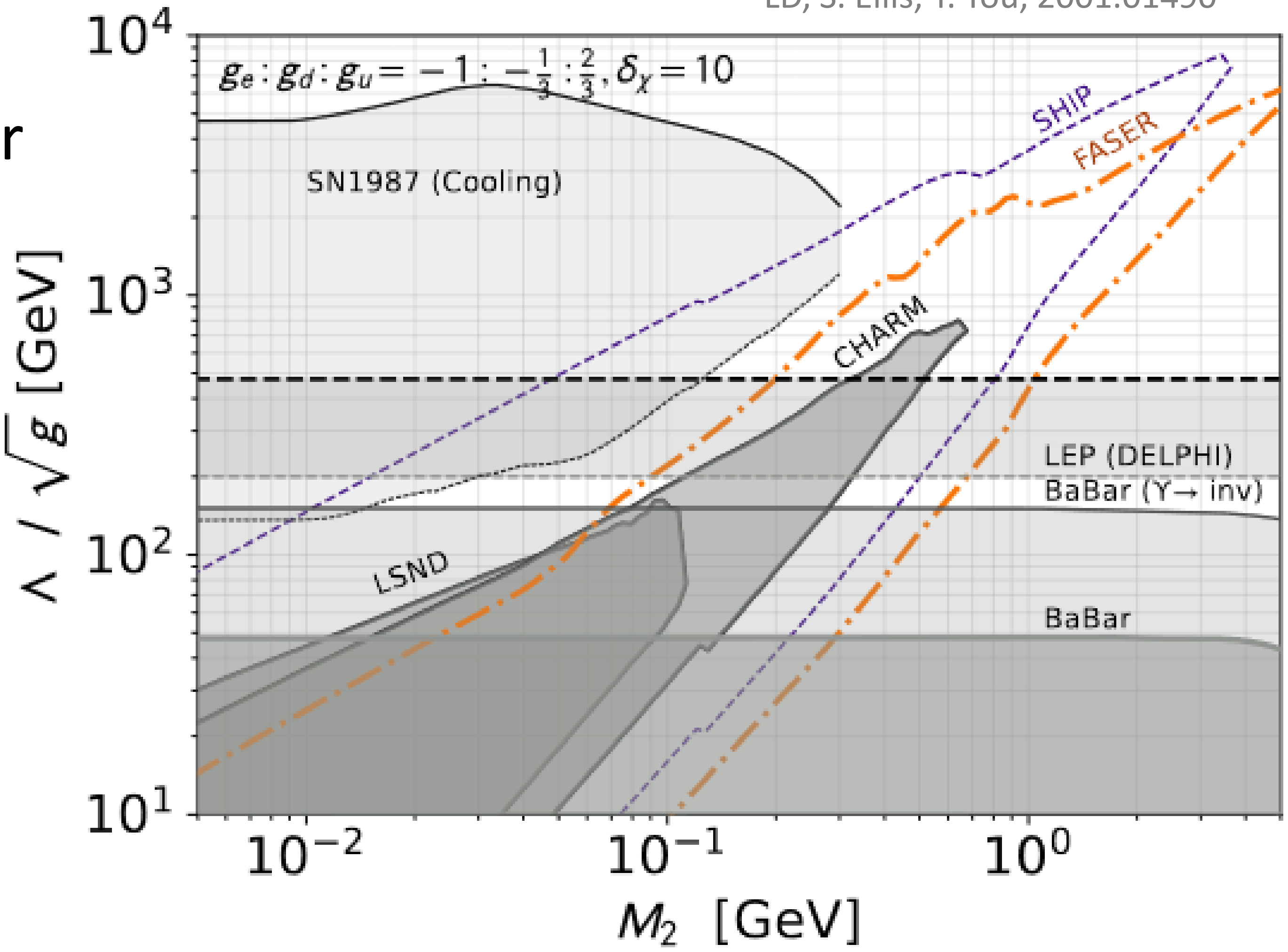


→ Include two states to allow for displaced searches

→Decay searches at saturation ($M_2 \gg M_1$) at LSND, CHARM, SeaQuest (hypothetical Phase 2 with $\sim 10^{18}$ PoT) and SHIP

→SN1987 cooling limits, but strong model dependence in the lower bounds (dark sector trapping)

LD, S. Ellis, T. You, 2001.01490



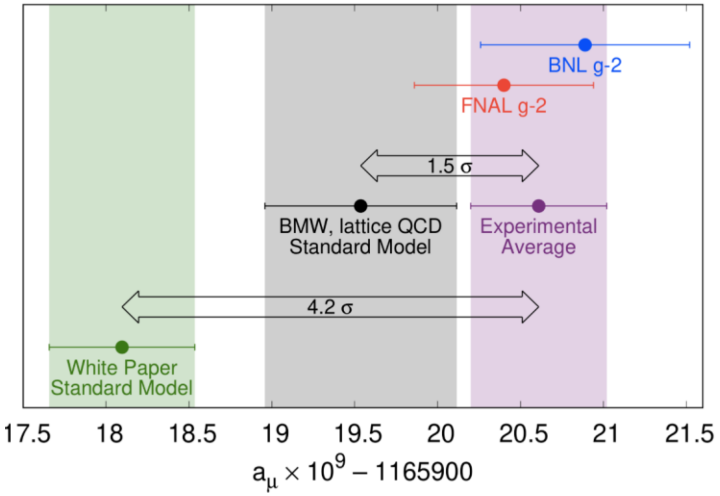
GeV-scale measurement for new physics: the status of HVP and $(g-2)_\mu$

Anomalous magnetic moment of the muon

- One of the oldest observable of "particle physics", followed the community since QED

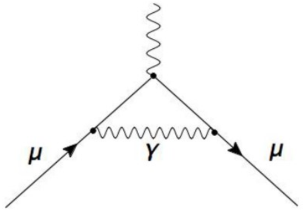
~5000 works referenced on Inspire …

From F. Jegerlehner's talk at g-2 days 2021



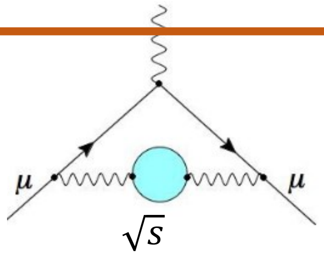
- Basically any model imaginable has been thrown at the long-standing anomaly in $(g-2)$
  - → From SUSY to light new particles Gninenko 2001, Baek 2001, Ma 2001… Brodsky 1967…

- SM prediction ?



$a_\mu \supset\ 116\,584\,71.89 \pm 0.01 \times 10^{-10}$

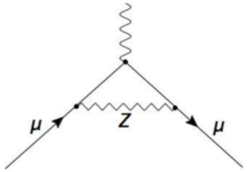
Pure QED



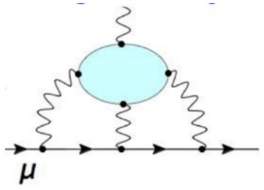
$a_\mu \supset 684.5 \pm 4.0 \times 10^{-10}$

Hadronic Vacuum Polarisation

$a_\mu \supset 15.36 \times 10^{-10}$



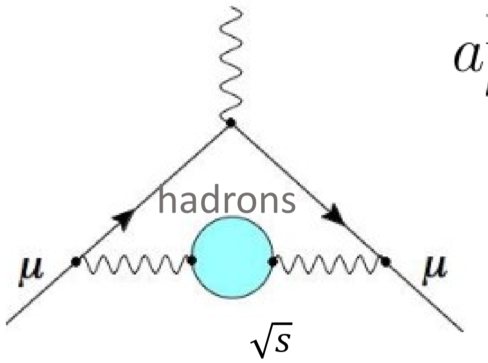
$a_\mu \supset 9.2 \times 10^{-10}$



EW , Light-by-light, etc…

The R-ratio data-driven a_μ^{HVP}

- The hadronic loop must be estimated for all scales (although dominated by sub-GeV scales)

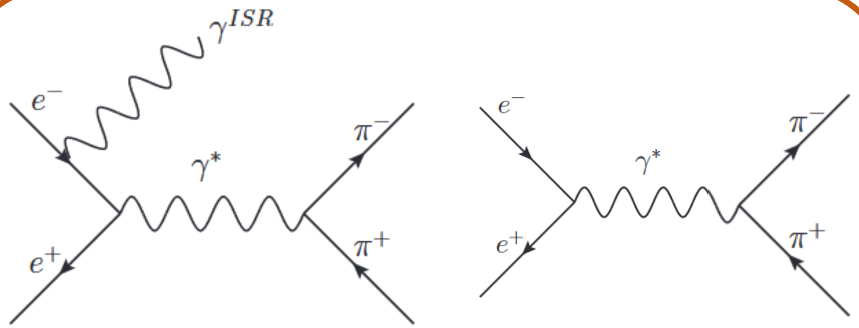


$$a_\mu^{\mathrm{LO,HVP}} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\, K(s)\,\sigma_{\mathrm{had}}(s)$$

Kernel function: skew the integrals toward smaller s

bare cross-section

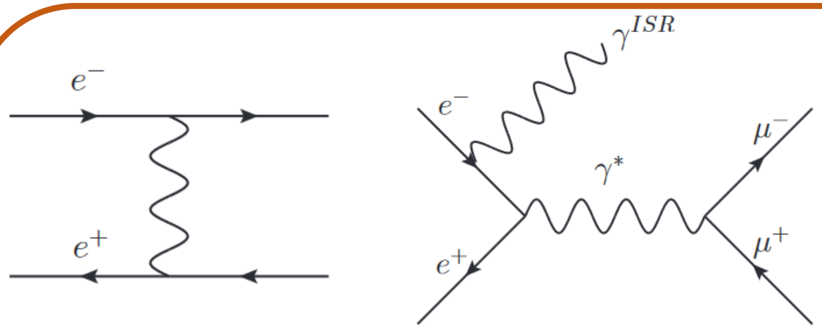
- Data is therefore required for $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma^* \rightarrow \pi\pi, 3\pi, KK, etc$ … AND for the normalisation channel fixing the experimental luminosity



Either point-per-point scan measurement of $\sqrt{s}$, or on-the-fly with ISR

$$\sigma_{\pi\pi}^{0,exp.} \propto \frac{N_{\pi\pi}^{\mathrm{All}}}{N_{e^+e^-}^{\mathrm{All}}}$$

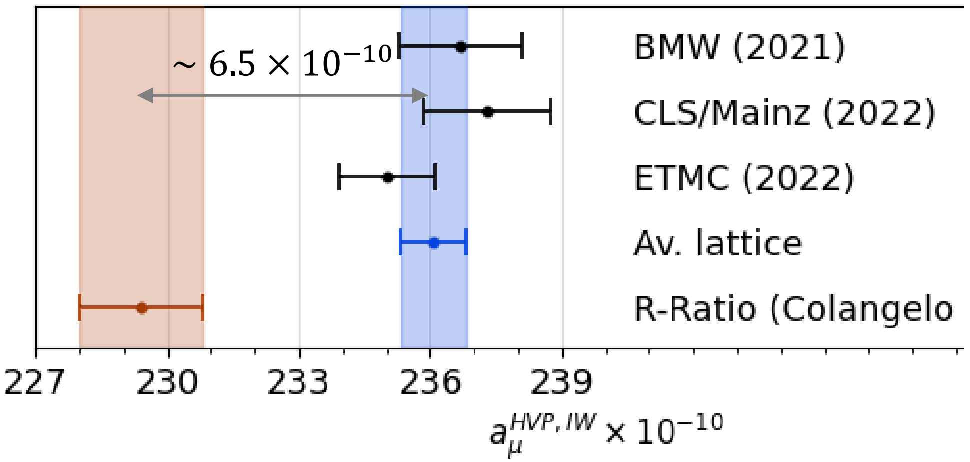
$$\sigma_{\pi\pi}^{0,exp.} \propto \frac{N_{\pi^+\pi^-\gamma_{ISR}}^{\mathrm{All}}}{N_{\mu^+\mu^-\gamma_{ISR}}^{\mathrm{All}}}$$



Various methods available for the luminosity estimates: Bhabha scattering, di-muon final states, etc…

Finding the HVP contributions

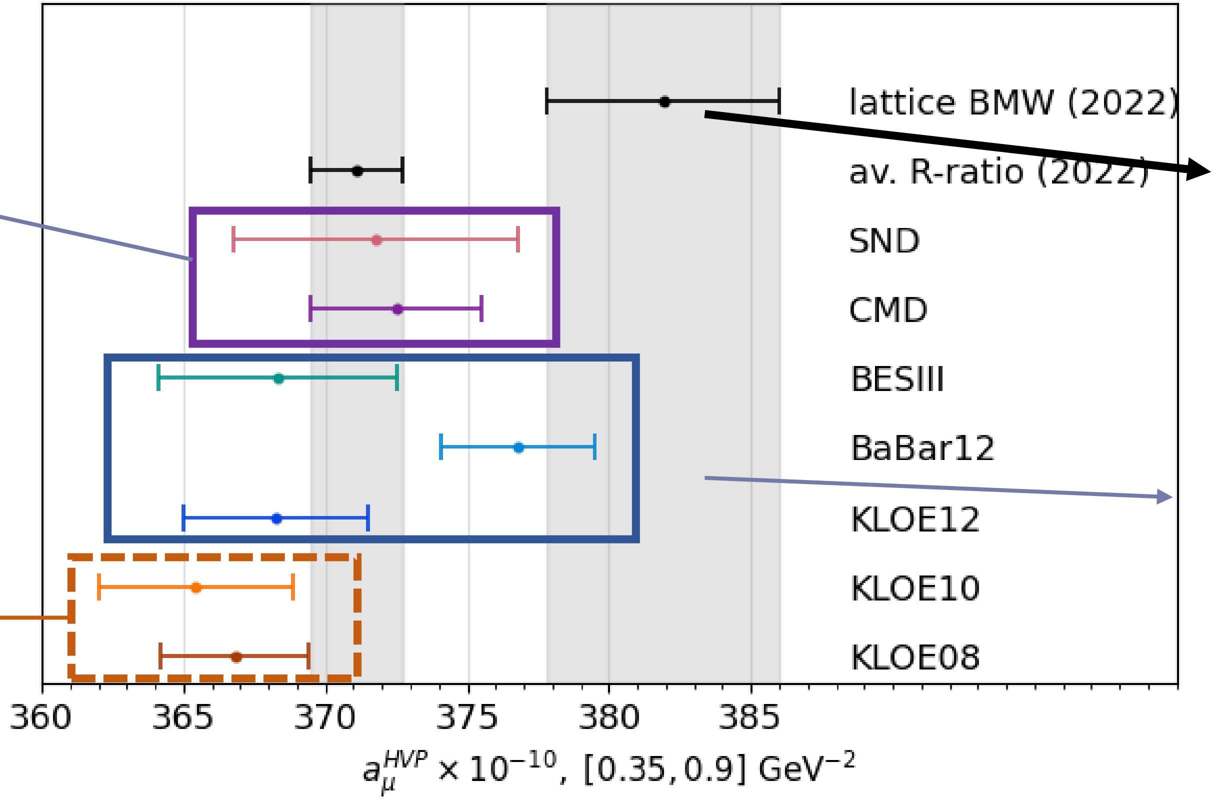
- Many experimental data required and combined for the above: very good control of GeV-scale physics required for new physics search



«Window» HVP result, were lattice should be the most precise
→ $0.75\ \text{GeV} \lesssim \sqrt{s} \lesssim 2.5\ \text{GeV}$

Troubling discrepancies with the lattice predictions …

Energy scan:
Bhabha scattering, no ISR



Newer analysis:
$\mu\mu\gamma$ for luminosity and ISR

Older analysis:
Bhabha scattering + ISR photon

GeV-scale data wanted …

- Two 4.2σ anomalies, with the discrepancy lattice vs data-driven apparently a pure GeV-scale effect
- New data at the GeV-scale is needed to confirm – or not – the presence of a UV-relevant anomaly

- More measurements and cross-checks

  → Belle-II, BESIII data to come

  → MuonE at CERN project: measure the $e\mu \to e\mu$ scattering to extract HVP from t-channel data

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

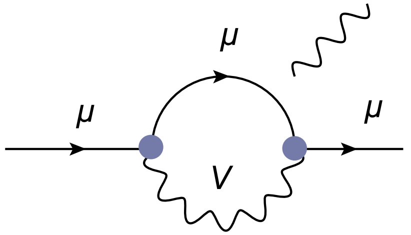
- New physics ?
- In general viable GeV-scale new physics solution of the a_μ will also have an indirect effect on the data-driven results …

New physics contribution to g-2

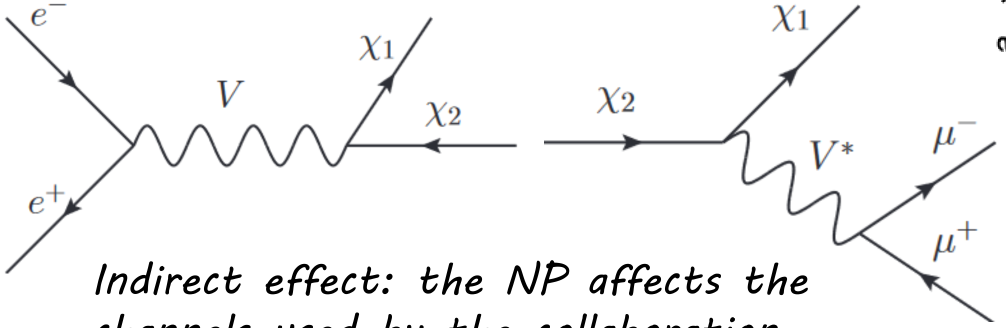
- Main idea: acts both on the actual a_μ via standard loop corrections AND to the R-ratio estimate

  →Affects the HVP R-ratio estimate by adding NP in the fitted datasets

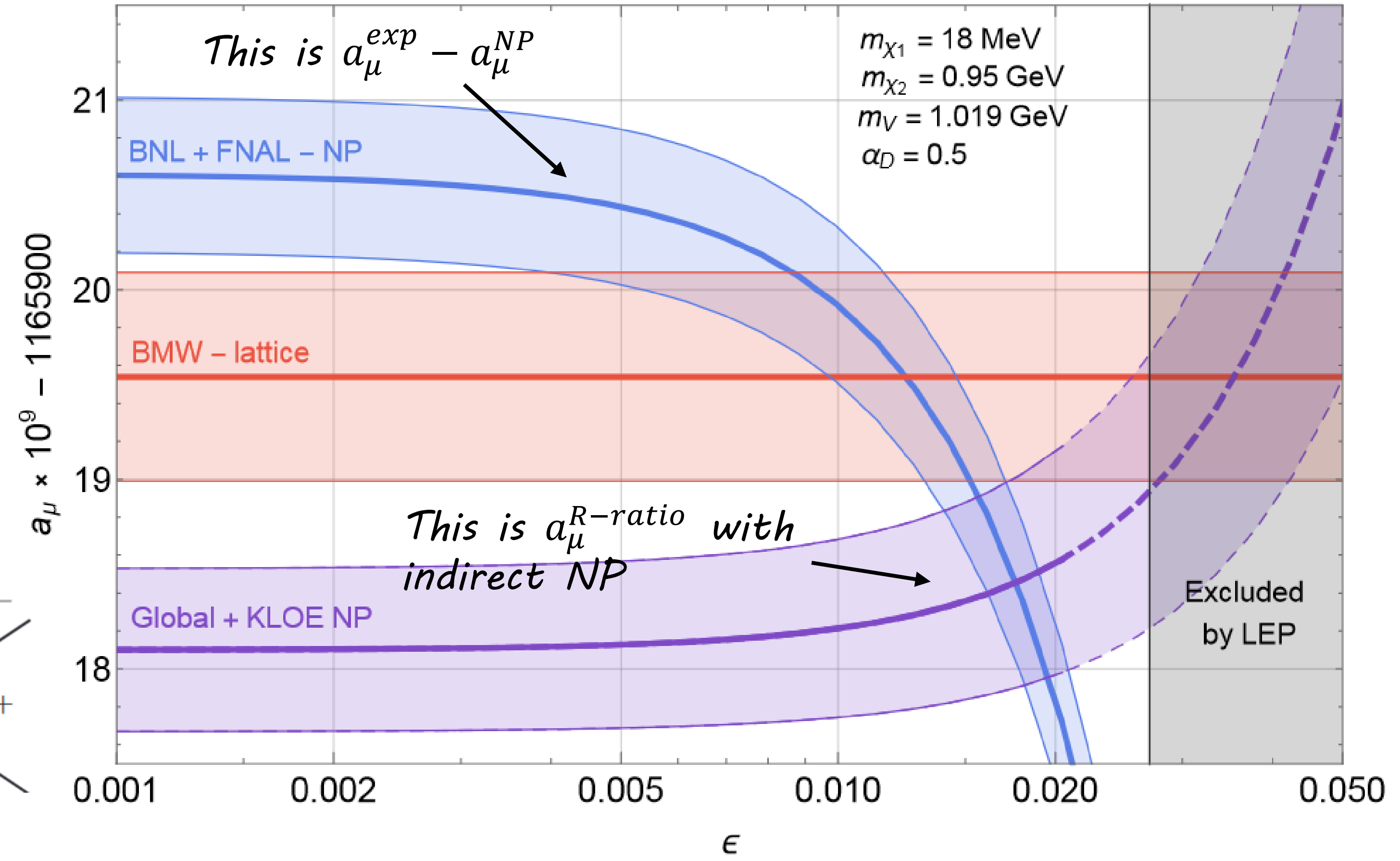
LD, Grilli di Cortona, Nardi, 2112.09139



Direct effect: the NP really impacts a_μ



Indirect effect: the NP affects the channels used by the collaboration to normalise their data

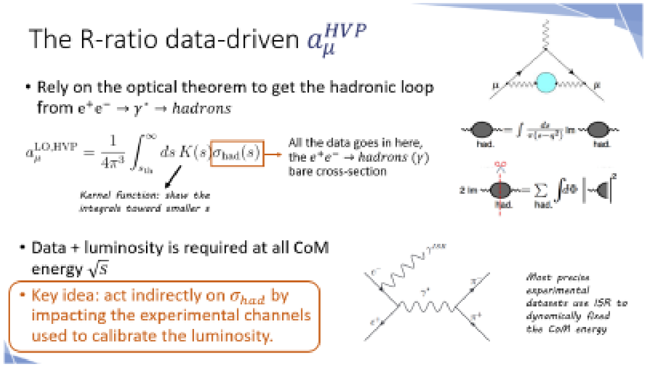


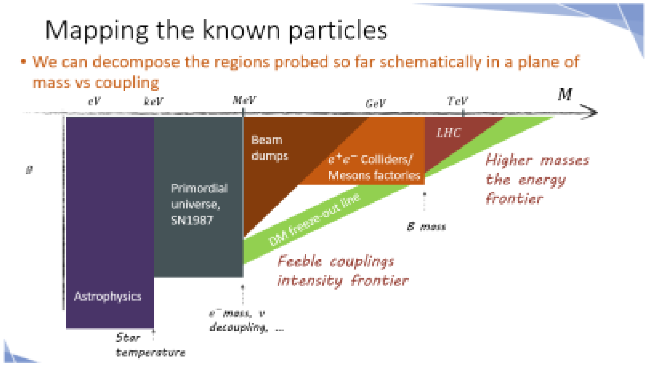
Conclusion

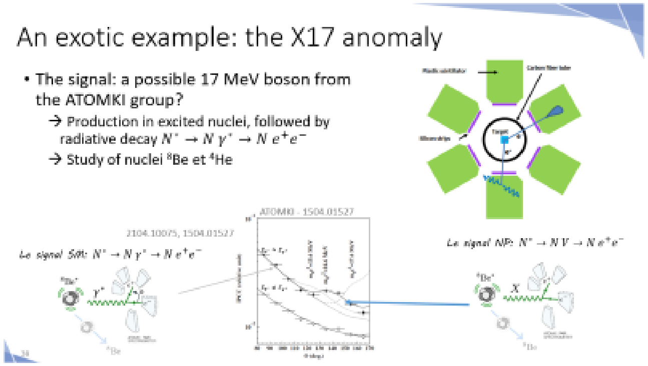
Conclusion

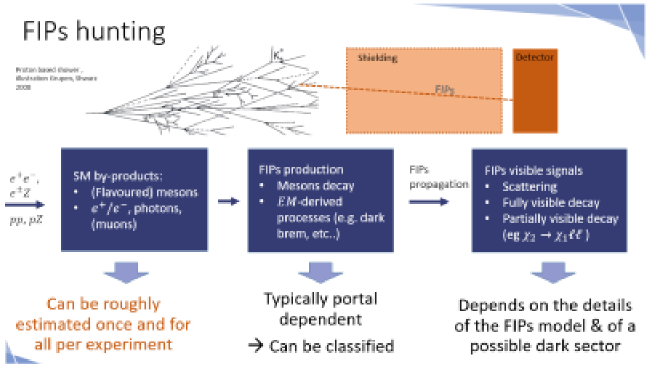
- Feebly-interacting particles can be searched for in an extremely large range of experiments
  - → Neutrinos : FIPs@DUNE, T2K, KM3Net, RICOCHET, SBN program
  - → Flavor : Belle-II, LHCb, KOTO, NA62
  - → High energy: LLP program at LHC, FASER and FPF program
- Their small interactions can either arise from tiny mixing, or from new UV structure
  - →For simple UV model, scales larges than 10^6 GeV can be probed, even in absence of flavour violation !
- New measurements at the GeV scale are still very much required, from the $g-2$ physics to flavour physics …

Backup

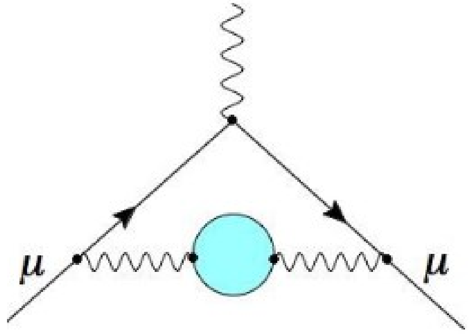

The R-ratio data-driven a_μ^{HVP}
Rely on the optical theorem to get the hadronic loop from $e^+e^- \to \gamma^* \to hadrons$
All the data goes in here, the $e^+e^- \to hadrons\ (\gamma)$ bare cross-section
Kernel function: skew the integrals toward smaller s
Data + luminosity is required at all CoM energy $\sqrt{s}$
Key idea: act indirectly on σ_{had} by impacting the experimental channels used to calibrate the luminosity.
Most precise experimental datasets use ISR to dynamically fixed the CoM energy


Mapping the known particles
We can decompose the regions probed so far schematically in a plane of mass vs coupling
eV
keV
MeV
GeV
TeV
M
Astrophysics
Primordial universe, SN1987
Beam dumps
e^+e^- Colliders/ Mesons factories
LHC
DM freeze-out line
Higher masses the energy frontier
Feeble couplings intensity frontier
B mass
e^- mass, ν decoupling, ...
Star temperature

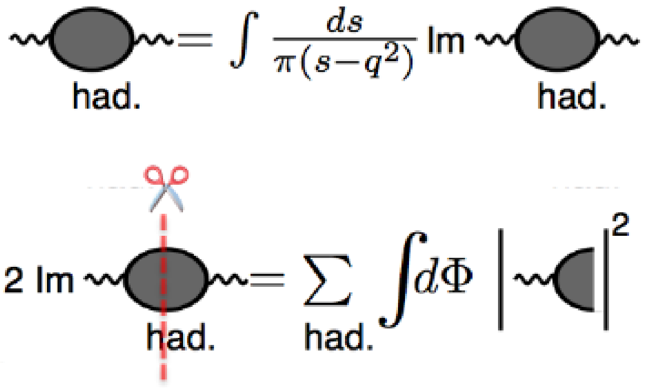

An exotic example: the X17 anomaly
The signal: a possible 17 MeV boson from the ATOMKI group?
→ Production in excited nuclei, followed by radiative decay $N^* \to N\gamma^* \to N e^+e^-$
→ Study of nuclei ^{8}Be et ^{4}He
ATOMKI - 1504.01527
2104.10075, 1504.01527


FIPs hunting
Shielding
Detector
FIPs
e^+e^-, e^+Z
pp, pZ
SM by-products:
(Flavoured) mesons
e^+/e^-, photons, (muons)
FIPs production
Mesons decay
EM-derived processes (e.g. dark brem, etc..)
FIPs propagation
FIPs visible signals
Scattering
Fully visible decay
Partially visible decay (eg $\chi_2 \to \chi_1 \ell\ell$)
Can be roughly estimated once and for all per experiment
Typically portal dependent
→ Can be classified
Depends on the details of the FIPs model & of a possible dark sector

The R-ratio data-driven a_μ^{HVP}



- Rely on the optical theorem to get the hadronic loop from $e^+e^- \to \gamma^* \to hadrons$

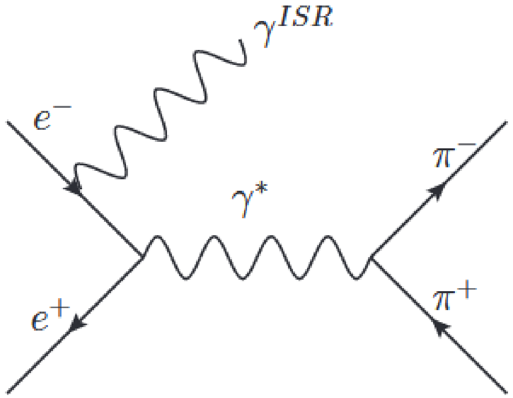


$$a_\mu^{\mathrm{LO,HVP}} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\, K(s)\, \sigma_{\mathrm{had}}(s)$$

All the data goes in here, the $e^+e^- \to hadrons\ (\gamma)$ bare cross-section

Kernel function: skew the integrals toward smaller s

- Data + luminosity is required at all CoM energy $\sqrt{s}$
- Key idea: act indirectly on σ_{had} by impacting the experimental channels used to calibrate the luminosity.



Most precise experimental datasets use ISR to dynamically fixed the CoM energy

SM at the GeV-scale

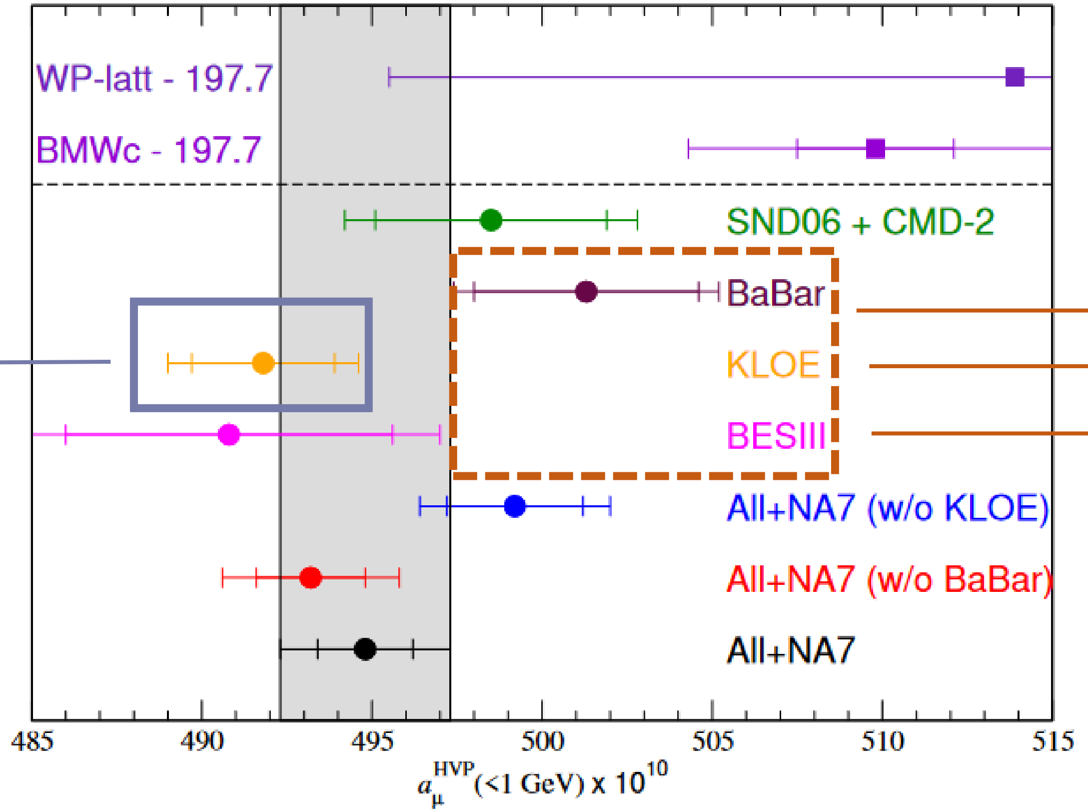
- The various analysis rely on different methods to calibrate their luminosity
  → Full experimental simulation required to find the efficiencies !

$$\delta_R = \frac{\sigma^{NP}_{e^-e^-}\,\epsilon^{NP}_{e^-e^-}}{\sigma^{0}_{e^-e^-}\,\epsilon^{SM}_{e^-e^-}}$$

Around 60 nb ! → ~nb CS required from NP

Faking Bhabha final states modifies KLOE08 and KLOE10

Hoferichter 2021 g-2 days



$$\delta_\mu(s') \equiv \frac{\sigma^{NP}_{\mu\mu X}(s')\,\epsilon^{NP}}{\sigma_{\mu\mu}(s')\,\epsilon^{SM}}$$

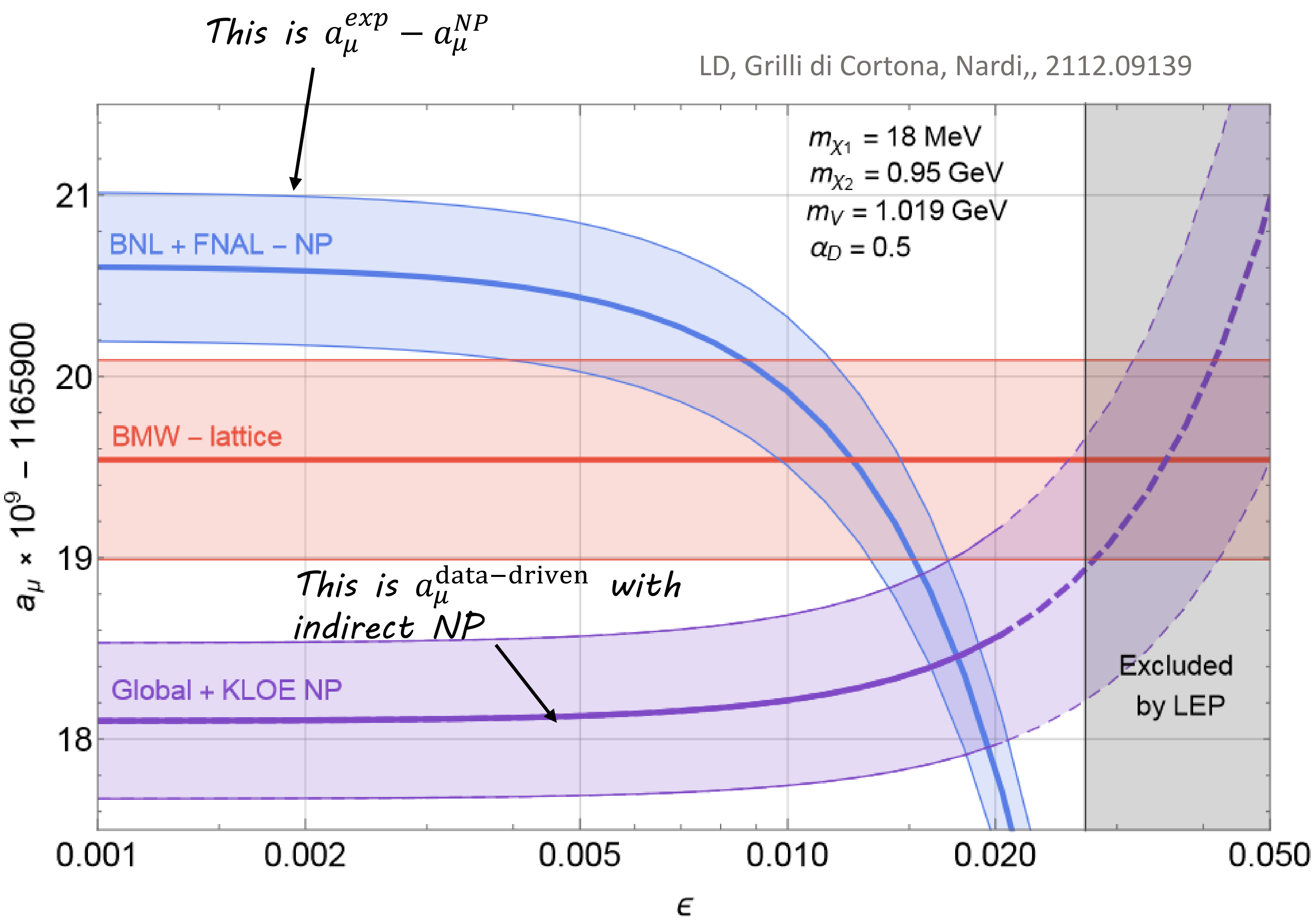
Around the nb, smaller CS required from NP

Faking di-muon final states modifies KLOE12, and BESIII (and BaBaR)

- Shifting the normalisation of the KLOE analysis using e^+e^- to calibrate the luminosity is much harder: will require a NP at *precisely* the KLOE energy.

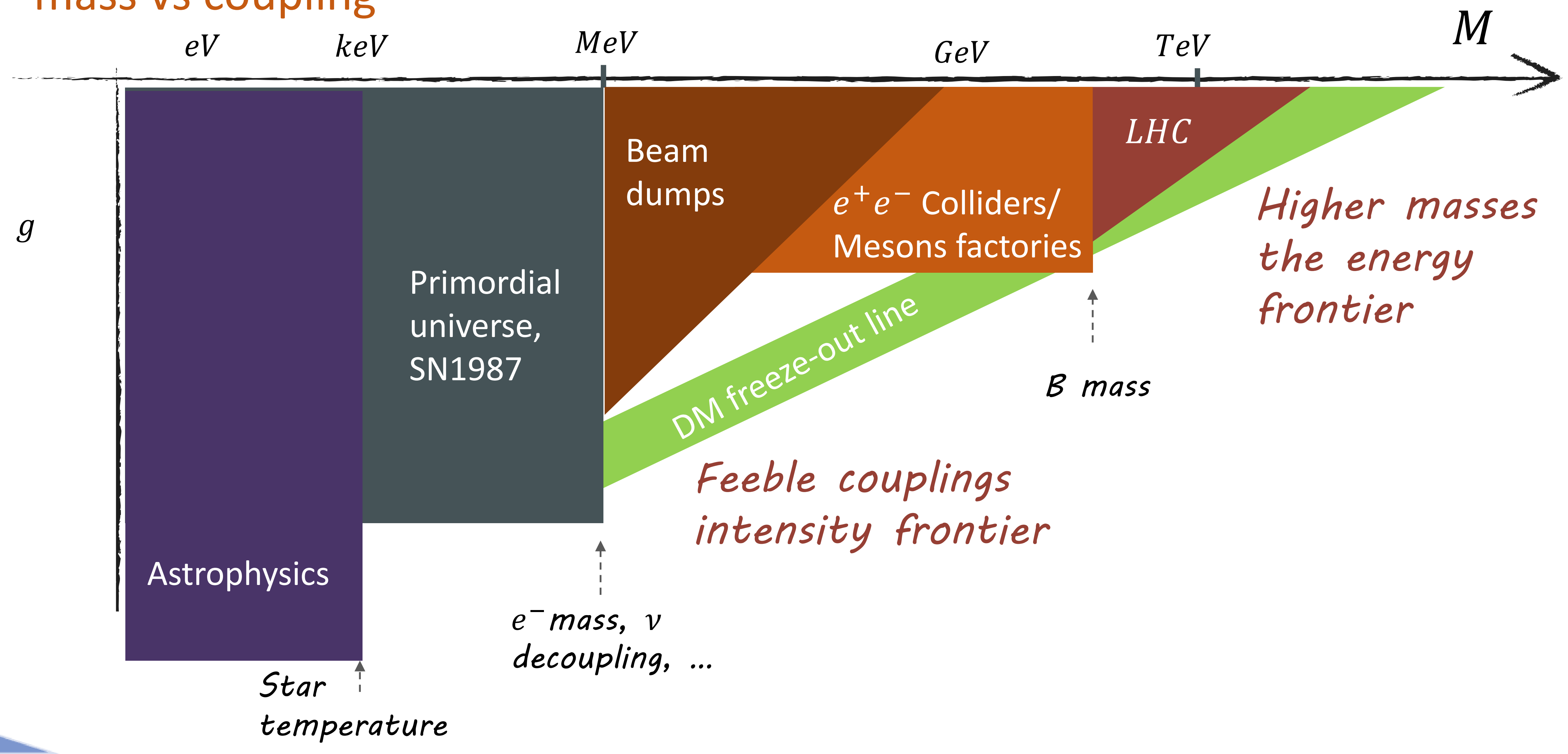
Example of result

- Resonant FIP production at KLOE is required to act on KLOE08
  - → $m_V \sim \sqrt{s_{KLOE}}$ helps but not requirement for lattice vs R-ratio
- Solve in one go all tensions in Δa_μ-related observables !
  - →Around 3/4 of Δa_μ from NP loop and 1/4 from this effect



Mapping the known particles

- We can decompose the regions probed so far schematically in a plane of mass vs coupling



FIPs: Feebly Interacting Particles

- FIPs= "new neutral particle which interacts with the SM via suppressed new interactions"

The hierarchy problem

What is the origin of flavour?

The nature of dark matter?

Origin of the ν masses?

Why does QCD respect CP ?

A good few dozens of anomalies

Axions, ALPs, LDM, dark photons, dark Higgs, HNL, hexaquark H, etc…

Searches and constraints in the MeV-GeV range mostly driven by low energy accelerators

Belle-II, NA62, KOTO,…
Mono-γ, Désintégration B,K rares, etc.

PADME, NA64, NA62, KOTO…
Light mesons decay & fixed targets

SBN, T2K, KM3Net, DUNE, JUNO
Light DM scattering, sterile neutrino & oscillations

ATLAS, CMS, ALICE, LHCb
(+ program LLP: FASER, Codex-B…)
LLP search, displaced vertex

Axion-like particle – dim 5

- An axion-like particle (ALP) a, interacts via two portal operators : $\bar{l}\gamma^{\mu}\gamma^{5}l$ and $F^{\mu\nu}\,\tilde{F}^{\mu\nu}$

$$\mathcal{L} \subset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \frac{1}{4}g_{a\gamma}a F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_{l=e,\mu,\tau}\frac{g_{al}}{2}(\partial_\mu a)\bar{l}\gamma^\mu\gamma^5 l$$

- We can "hide" the ALP via a coupling to a dark current $\mathcal{L} \supset \frac{g_{a\chi}}{2}(\partial_\mu a)\mathcal{J}^{\mu}_{5,D}$
- Origin: approximate symmetry in Higgs UV sector
  - →Typical ALP model arise as pNGB from a bigger scalar sector, with mass term protected by an approximate global symmetry
  - →Coupling can be represented either in Yukawa or "derivative form", in both cases, large couplings must arise from small scale VEVs.

$$\mathcal{L}_R^{\rm eff} = \frac{1}{2}\partial_\mu a^0\partial^\mu a^0 - i\sum_{f=u,d,e}\frac{m_f}{v_a}\chi_P^f\, a^0\bar{\psi}_f\gamma_5\psi_f\ ,$$

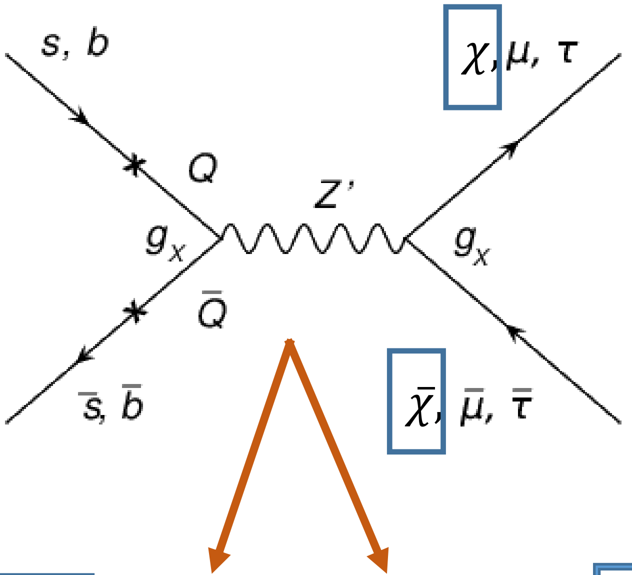
⟺

$$\mathcal{L}_{NR}^{\rm eff} = \frac{1}{2}\partial_\mu a^0\partial^\mu a^0 - \frac{\partial_\mu a^0}{2v_a}\sum_{f=u,d,e,\nu}\left(\chi_V^f\ \bar{\psi}_f\gamma^\mu\psi_f + \chi_A^f\ \bar{\psi}_f\gamma^\mu\gamma_5\psi_f\right) + \frac{a^0}{16\pi^2 v_a}\left(g_s^2 N_C^{eff} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 N_L^{eff} W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 N_Y^{eff} B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

Dimension 6 operators

- Following the example of neutrinos: fermions portal are straightforwardly obtained if new UV theories with a light dark sector.

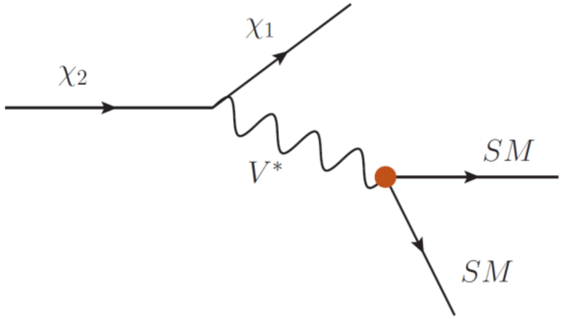
  → E.g. new vector mediator for LHCb flavour anomalies,
  replace the muons with a dark fermion



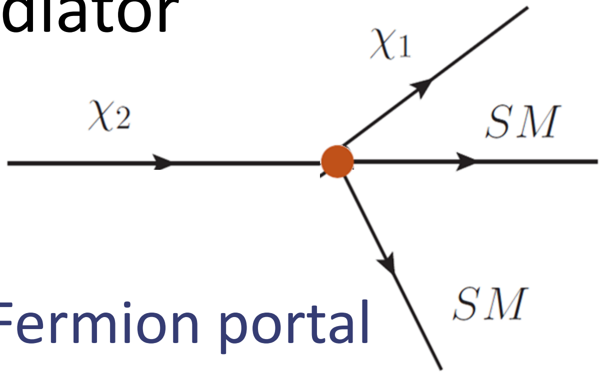
$\bar{\chi}\gamma^{\nu}\chi\,\bar{\mu}\,\gamma_{\nu}\mu$ $\qquad$ $\bar{b}\gamma^{\nu}P_{L}s\,\bar{\chi}\,\gamma_{\nu}\chi$

$O_9 \sim \bar{b}\gamma^{\nu}P_{L}s\,\bar{\mu}\,\gamma_{\nu}\mu$

- Another example inelastic dark matter setups, where a GeV-scale state decay into a lighter one (e.g. dark matter) via a heavy mediator



Integrate out V^* →



Fermion portal

Non-conserved currents

- Interactions via non-conserved SM currents leads to strong signatures at small vector masses (Goldstone equivalence, high-energy processes scale as $\frac{E^2}{M_V^2}$)

Pospelov, Dror, Lasenby

$$V_\mu \to \frac{1}{M_V}\partial_\mu V_L$$

$$\mathcal{L}_{\rm int} \supset V_\mu \mathcal{J}_V^\mu \quad \Rightarrow \quad \mathcal{L}_{\rm int} \supset \frac{V_L}{M_V}\partial_\mu J_V^\mu$$

If the current does not correspond to a SM global symmetry, $\partial_\mu J_V^\mu \neq 0$

Note that applying the full Ward identities also leads to anomalous boson interactions

- Apart from few decently protected examples, most current have, e.g.
  - →Tree-level flavour violation, both critical to the anomalies and very strongly constrained
  - →Weak-isospin violation (no coupling to neutrinos)
  - →Axial-coupling interaction to the SM fermions
- The interaction rates are then dominated by the dimension-5, UV-dependent interaction
- Anomaly cancellations may also introduce non-decoupling chiral fermions

Long-lived particle search

- For long-lived particle, the propagation length is a critical parameter, since once the FIP is produced, it must additionally decay within the detector

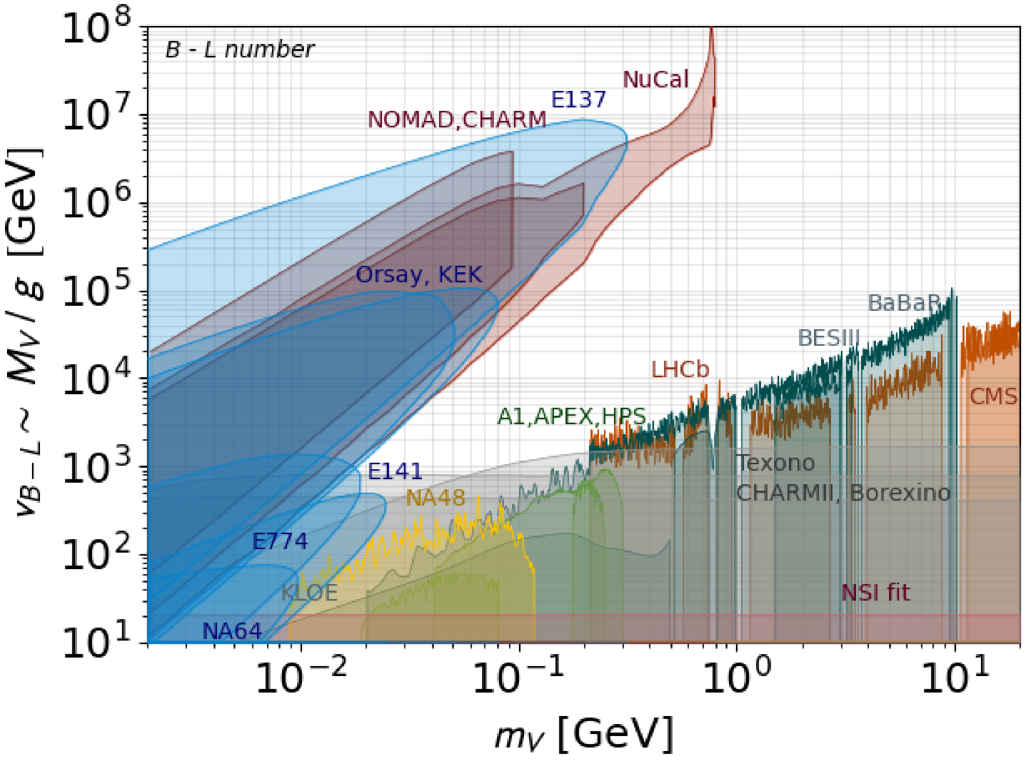
$$\mathcal{P}_{\rm CHARM} = \epsilon_{\rm geom} e^{-D/\ell_V} (1 - e^{-L/\ell_V}) \qquad \ell_V = \frac{\hbar c E}{\Gamma m_V} \sim 10\ {\rm m} \times \left(\frac{\gamma_V}{1000}\right) \left(\frac{1 \cdot 10^{-5}}{\varepsilon}\right)^2 \left(\frac{0.1\ {\rm GeV}}{m_V}\right)$$

$$D = 487{\rm m} \qquad L = 35{\rm m}$$

- Clearly, the best case scenario is when the decay length is of the order of the detector distance $\ell_V / D \sim 1$

- At very small coupling, the lifetime becomes too long

$$N_{decay} = N_V \times \mathcal{P}_{\rm CHARM} \sim 20\, \epsilon_{\rm geom} \left(\frac{500}{\gamma_V}\right) \left(\frac{\varepsilon}{1.5 \cdot 10^{-7}}\right)^4 \left(\frac{m_V}{50\ {\rm MeV}}\right)$$



Anomalies: (non-exhaustive) list

ASTROPHYSICS/COSMO

- Low primordial Li^7 (e.g 1203.3551) → Decaying FIP …
- Magnificent Seven (e.g 1910.04164) → Axions…
- Stellar cooling hints (e.g. 2003.01100) → Axions…
- Xenon 1T e-scattering (2006.09721) → LDM, keV dark photon
- Hubble rate tension (2103.01183) → Decaying DM, axion, …
- DM small-scale (e.g. 1912.06681) → LDM with FIP mediator

PRECISION/NEUTRINOS

- Proton charge radius (e.g 1502.05314) → Scalar/vector FIP …
- $(g-2)_{e,\mu}$ (e.g. 2006.04822 and 1812.04130, Morel 2020) → Scalar/vector FIP …
- Atomki X17 (1910.10459) → Scalar/vector FIP …
- MiniBooNE ν_e excess (e.g 1812.08768) → ν_R+ light FIPs

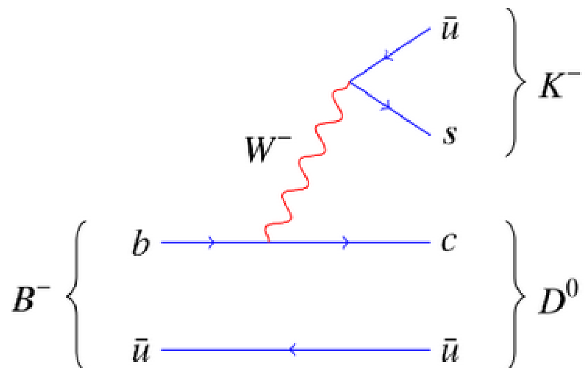
SAVEUR

- $b \to s$ et $b \to c$ non-universalité (e.g 1807.11373) → FIP + UV physics
- CKM non-unitarité (e.g 2103.05549)
- KOTO $K_L \to \pi^0 inv.$ anomalie (1910.07148) → Scalar FIP
- Kaons CPV ratios and ΔA_{CP} in D^0 (e.g. 1911.06211)

High-energy

- Hints in top-observables (e.g. 2011.06514) → Sub-EW scale top-philic particle

Flavourful SM mesons decays



- Transitions between quarks generations in the SM are thus strongly suppressed by
  → Heavy W boson mass + a factor of CKM suppression

- Long life-time allows to search for rare processes, since
  → Enhancement of the branching ratios
  → Potential study of "pure"mesons beams , e.g. for Kaons

$$\mathrm{BR}\,(B \to \mathrm{rare}) = \frac{\tau_B \Gamma_{\mathrm{rare}}}{\hbar}$$

Di Luzio et al. 2003.01100

Decay	Branching ratio	Experiment/Reference	f_a (GeV)
$K^+ \to \pi^+ a$	$< 0.73 \times 10^{-10}$	E949+E787 [593]	$> 3.4 \times 10^{11}\, \lvert C^V_{sd} \rvert$
$B^\pm \to \pi^\pm a$	$< 4.9 \times 10^{-5}$	CLEO [596]	$> 5.0 \times 10^{7}\, \lvert C^V_{bd} \rvert$
$B^\pm \to K^\pm a$	$< 4.9 \times 10^{-5}$	CLEO [596]	$> 6.0 \times 10^{7}\, \lvert C^V_{bs} \rvert$
$D^\pm \to \pi^\pm a$	< 1		$> 1.6 \times 10^{5}\, \lvert C^V_{cu} \rvert$
$\mu^+ \to e^+ a$	$< 2.6 \times 10^{-6}$	TRIUMF [598]	$> 4.5 \times 10^{9}\, \lvert C^{V(A)}_{\mu e} \rvert$
$\mu^+ \to e^+ \gamma a$	$< 1.1 \times 10^{-9}$	Crystal Box [600]	$> 1.6 \times 10^{9}\, C_{\mu e}$
$\tau^+ \to e^+ a$	$< 1.5 \times 10^{-2}$	ARGUS [604]	$> 0.9 \times 10^{6}\, C_{\tau e}$
$\tau^+ \to \mu^+ a$	$< 2.6 \times 10^{-2}$	ARGUS [604]	$> 0.8 \times 10^{6}\, C_{\tau \mu}$

For an axion/ALP with order one flavourful interactions

$$\mathcal{L}_{a f_i f_j} = -\frac{\partial_\mu a}{2 f_a} \left[\bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} - C^A_{f_i f_j} \gamma_5 \right) f_j \right]$$

If no suppression → extremely large scales can be probed

A peculiar case: new light gauge bosons

- Given the SM fermionic content: can we add a new gauge interactions ?

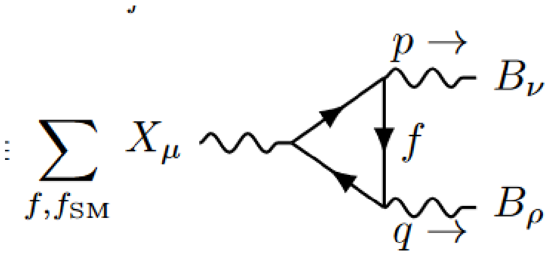
  →Main constraints are from gauge anomalies

Extracted from 2011.12973

Anomaly	Charge combinations
$U(1)^3_X$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$
$U(1)^2_X U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$
$U(1)_X U(1)^2_Y$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$

  →Only $L_{\ell_i} - L_{\ell_j}$ works !

Here is not the place to discuss at length anomalies … check them again in your favourite QFT book ☺



Note that we may have heavy new fermion cancelling out anomalies … at a price, see Dror, Pospelov, Lasenby 1705.06726

- Including ν_R (aka new fermionic FIP) + different charges per generations

  → e.g. $B - L$, $B - 3L_\tau$, etc…

2107.0792, Allanach et al.

for integer charges between -10 and 10 for 18 chiral fermion gauge representations in the SM plus three RH neutrinos were found by a scan.[4] Cases which are in a sense equivalent (where the charges differ by a common multiple which can be absorbed into the $u(1)_X$ gauge coupling, or which differ by a permutation of the family indices within a *species* - fields which have identical SM representations) were only counted once (and aside from some rare cases, only scanned over once). Anomaly-free solutions are scarce: only roughly one in 10^9 was anomaly-free from the whole sample. The list of anomaly-free fermionic charge assignments was made publicly available. It is a list of over 21 000 000 solutions that is easy and quick

From top to bottom and back

TeV
~100 GeV
GeV
MeV

UV theory,
from flavour,
hierarchy problem

Standard Model
Q_L, u_R, d_R, L, e_R
W, Z, h, FIP ?

Mesons, $e^{\pm}, \gamma, \nu$...
FIP ?

Top-down

- Integrating heavy states (SMEFT + X)
- Treating chiral fermions + anomalies
- Flavour structures
- Checking no dominant productions

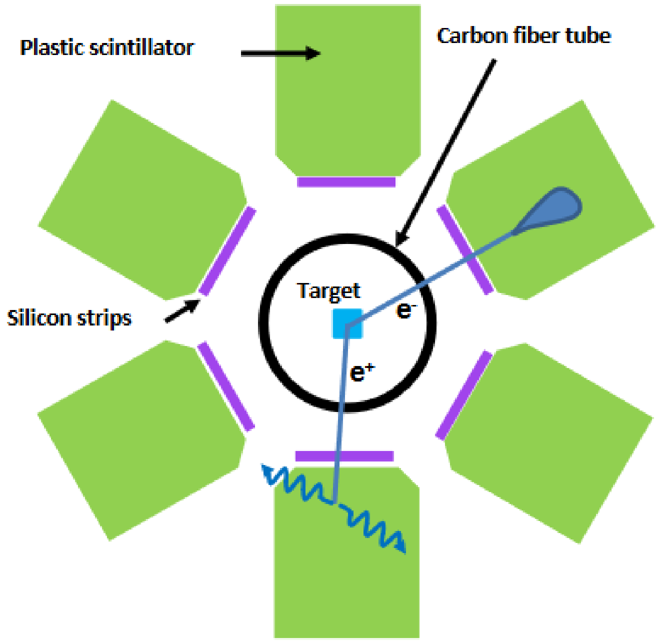
FIP models must also be consistent at this scale !

Bottom-up

- Coupling to the full SM does not trigger
  → new interactions, e.g. neutrinos
- χPT to describe the interaction with mesons
- Flavour violation with RGE running.

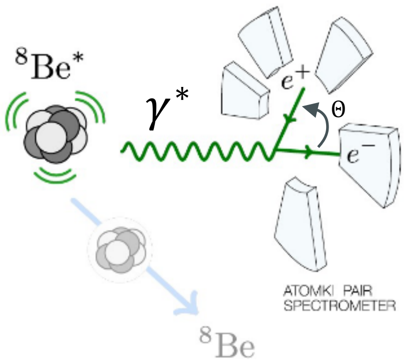
An exotic example: the X17 anomaly

- The signal: a possible 17 MeV boson from the ATOMKI group?
  - → Production in excited nuclei, followed by radiative decay $N^* \to N\,\gamma^* \to N\,e^+e^-$
  - → Study of nuclei ^{8}Be et ^{4}He

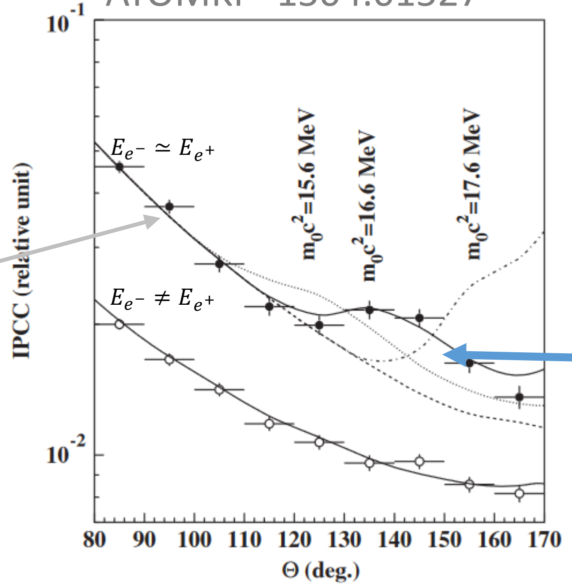


2104.10075, 1504.01527

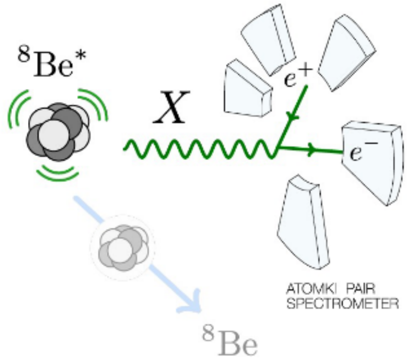
Le signal SM: $N^* \to N\,\gamma^* \to N\,e^+e^-$



ATOMKI - 1504.01527

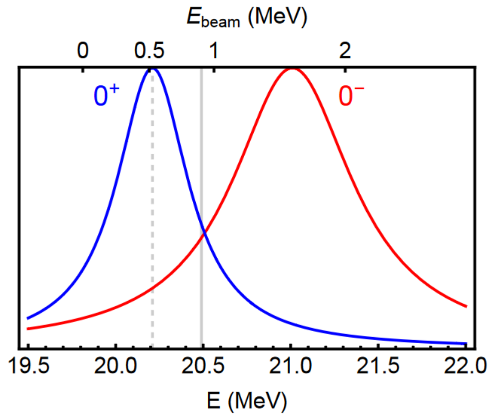


Le signal NP: $N^* \to N\,V \to N\,e^+e^-$



New physics candidates

- No current nuclear physics explanation
- A basic spin-parity analysis gives already hints of the proper candidate
  - →0+ : scalar excluded by Be data
  - →Sadly, He data runs in the middle of the two resonance



N_* \ X	0^+	0^-	1^-	1^+
^{4}He 0^+	S	—	—	P
^{4}He 0^-	—	S	P	—
^{12}C 1^-	P	—	S, D	P
^{8}Be 1^+	—	P	P	S, D

$$J_* = L \oplus J_X$$
$$P_* = (-1)^L P_X$$

- The requirements on the X17 are
  - →Large couplings to quarks $|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$
  - →Sizeable electron couplings to allow decay $\varepsilon_e > 10^{-5}$
  - →Small coupling to π^0 to escape NA48 limits $Q_u\varepsilon_u + Q_d\varepsilon_d \simeq 0$
  - →Very precise mass window

$$M_X = \begin{cases} 17.01 \pm 0.16 \text{ MeV} & (^8\text{Be [1,3]}) \\ 16.94 \pm 0.12 \text{ (stat)} & \\ \quad\quad \pm 0.21 \text{ (syst) MeV} & (^4\text{He [2]}) \end{cases}$$

What's next ?

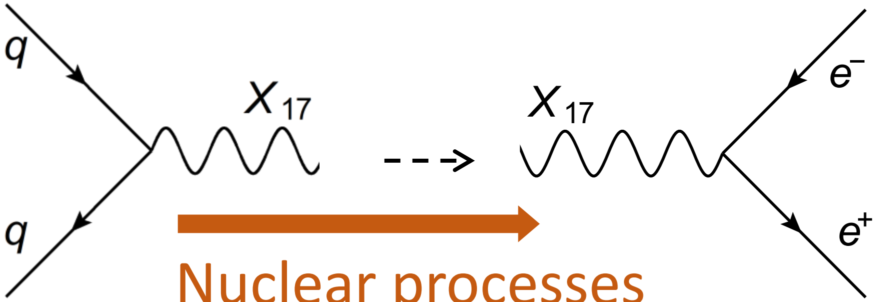
→ A clear signal (« bump » in e^+e^- spectrum) $\gg 5\sigma$

→ Two measurements with anomalies + upgraded exp.

→ One experimental group, some history of spurious claims

→ Complex theoretical construction (π^0-phobia)

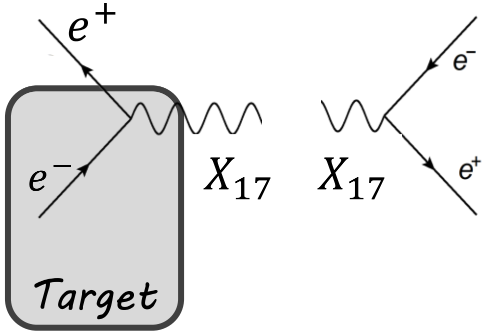
- Clearly experiment confirmation is needed
  - →Legnaro,New Jedi (GANIL), MEG
  - →MAGIC, Mu3e, NA64, etc…



Nuclear processes
Mesons decays

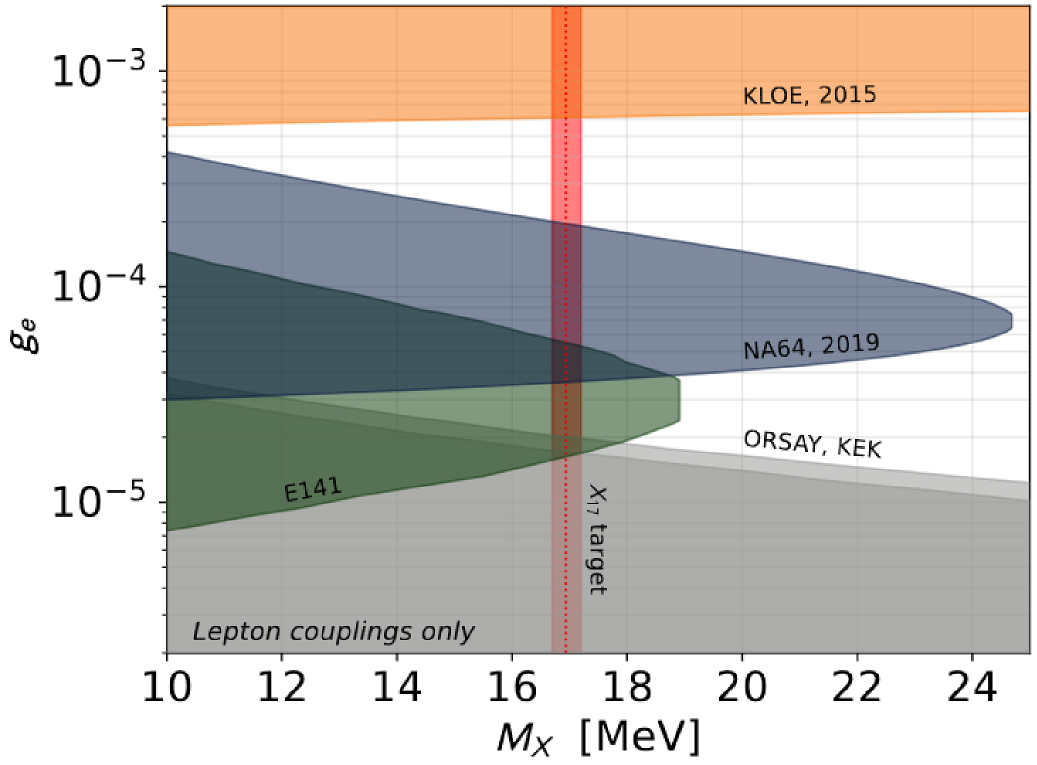
e^+/e^- « beam dump » and colliders e^+/e^-

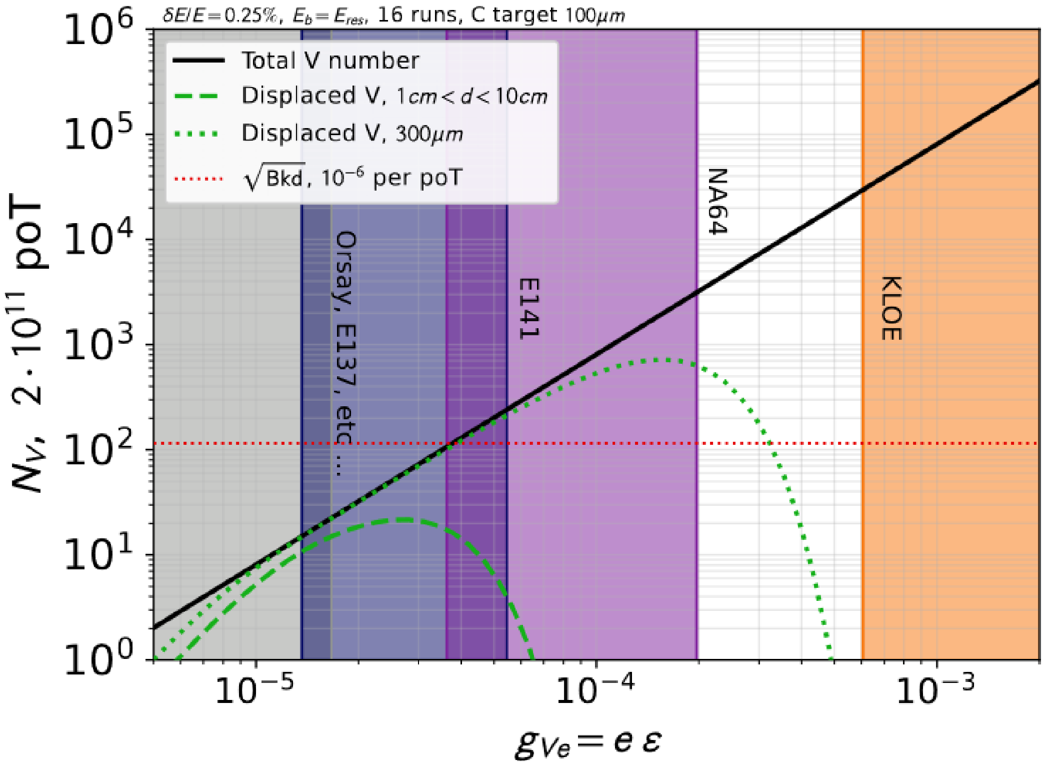
- Using lepton processes to check if this is really a new particle (and not some uncontrolled nuclear effect)
  - → The mass is known very precisely: possible use of resonant production $e^+e^- \to X_{17}$ with e^+ beam at $E_{res}^{X17} \simeq 280$ MeV



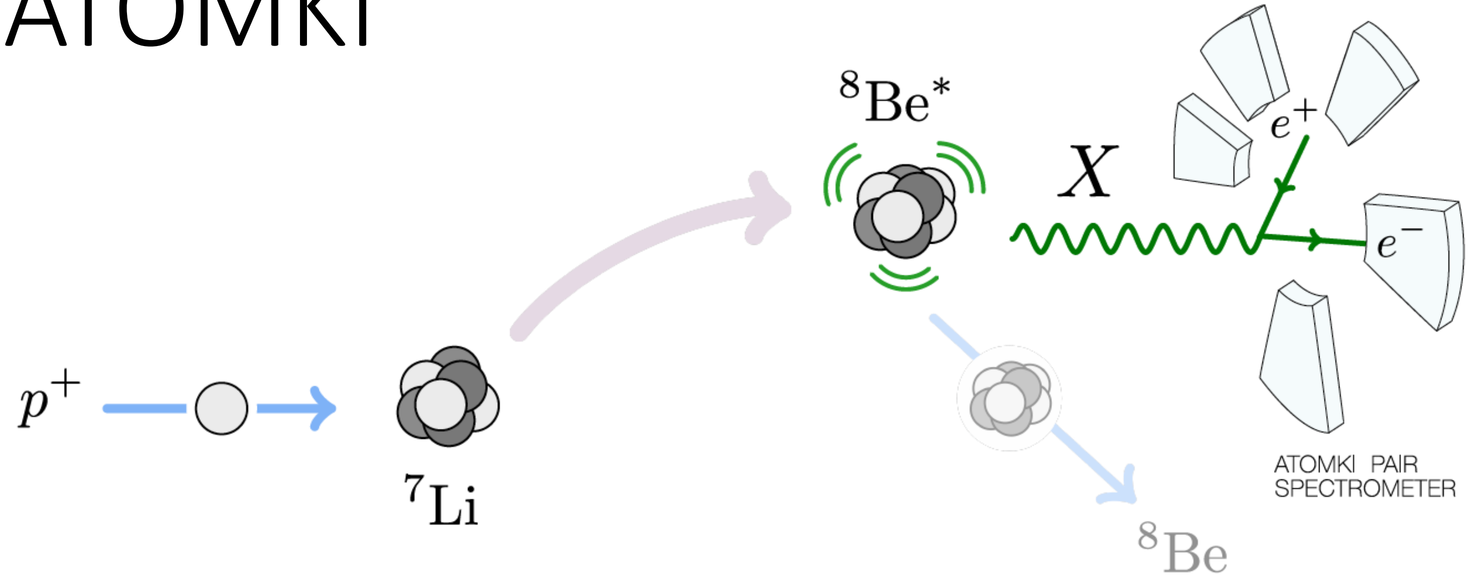
Lepton coupling: constraints

- On the lepton couplings side, the situation is quite clear
  - →Only a small window left for sizeable couplings
  - →Should be easily covered by a resonant search strategy at LNF in the next year



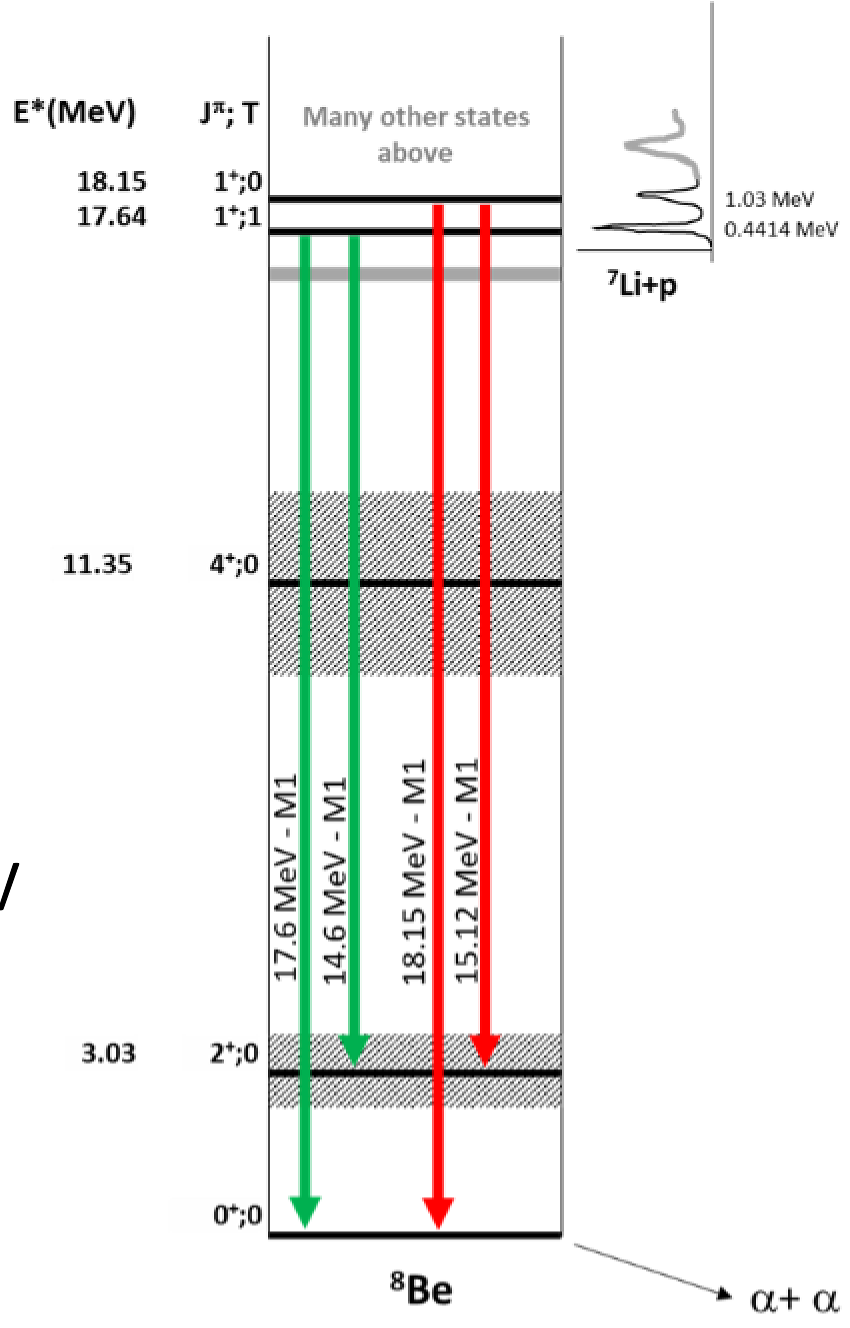


ATOMKI



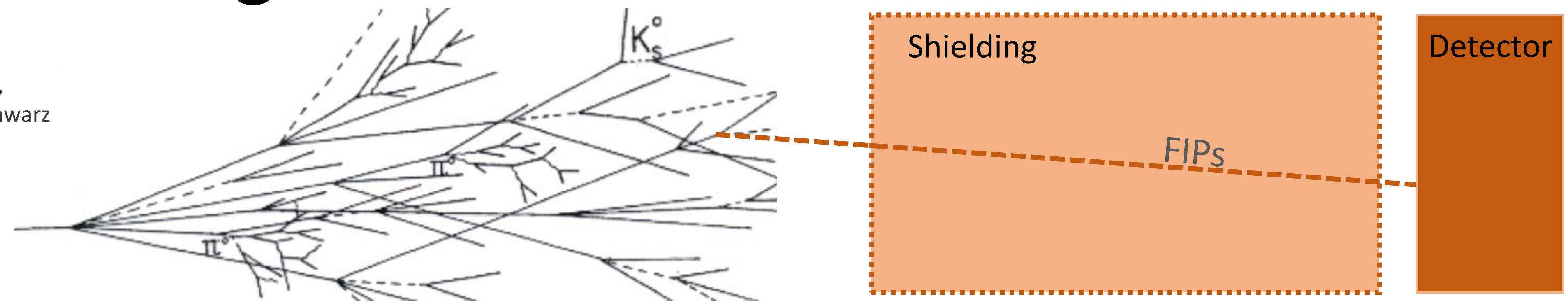
- Étude de la transition M1 de Be, avec création de pair B(8Be + e+ e-) ≈ 5.5 x 10-8
- Selectively populate the 17.64 MeV and 18.15 MeV resonances.

Reaction	$M_{X17} \pm \Delta M_{stat} \pm \Delta M_{syst}$ (MeV)	Statistical evidence
$^7Li(p,e^+e^-)^8Be$	16.70±0.35±0,50	>5 sigma
$^3H(p,e^+e^-)^4He$	16.94±0.12±0.21	>9 sigma



FIPs hunting

Proton based shower , illustration Grupen, Shwarz 2008



e^+e^-, $e^\pm Z$

pp, pZ

SM by-products:
- (Flavoured) mesons
- e^+/e^-, photons, (muons)

FIPs production
- Mesons decay
- EM-derived processes (e.g. dark brem, etc..)

FIPs propagation

FIPs visible signals
- Scattering
- Fully visible decay
- Partially visible decay (eg $\chi_2 \rightarrow \chi_1 \ell\ell$)

Can be roughly estimated once and for all per experiment

Typically portal dependent

→ Can be classified

Depends on the details of the FIPs model & of a possible dark sector

Accurate SM description for FIPs

e^+e^-, pp →

- Direct production
- Parton showers to mesons

$e^\pm Z, pZ$ →

- Hadronic showers (+ sub-EM showers)
- EM showers

- For mesons, typically the distributions in energy/polar angles are needed $f_M(\theta_M, E_M)$
- For $\gamma, e^+/e^-$ descriptions of EM showers, differential track lengths $T_{\gamma,e^\pm}(\theta, E)$: ("Total travelled distance in the target by all $\gamma, e^\pm$")

$$\mathcal{N}_{\rm FIP} \sim \frac{\mathcal{N}_A \rho_{\rm tar}}{A_{\rm tar}} \times T_{e^\pm,\gamma} \times \sigma_{\rm FIP}$$

$T_{\gamma,e^\pm}(\theta, E)$, $f_M(\theta_M, E_M)$ can be be typically obtained via:

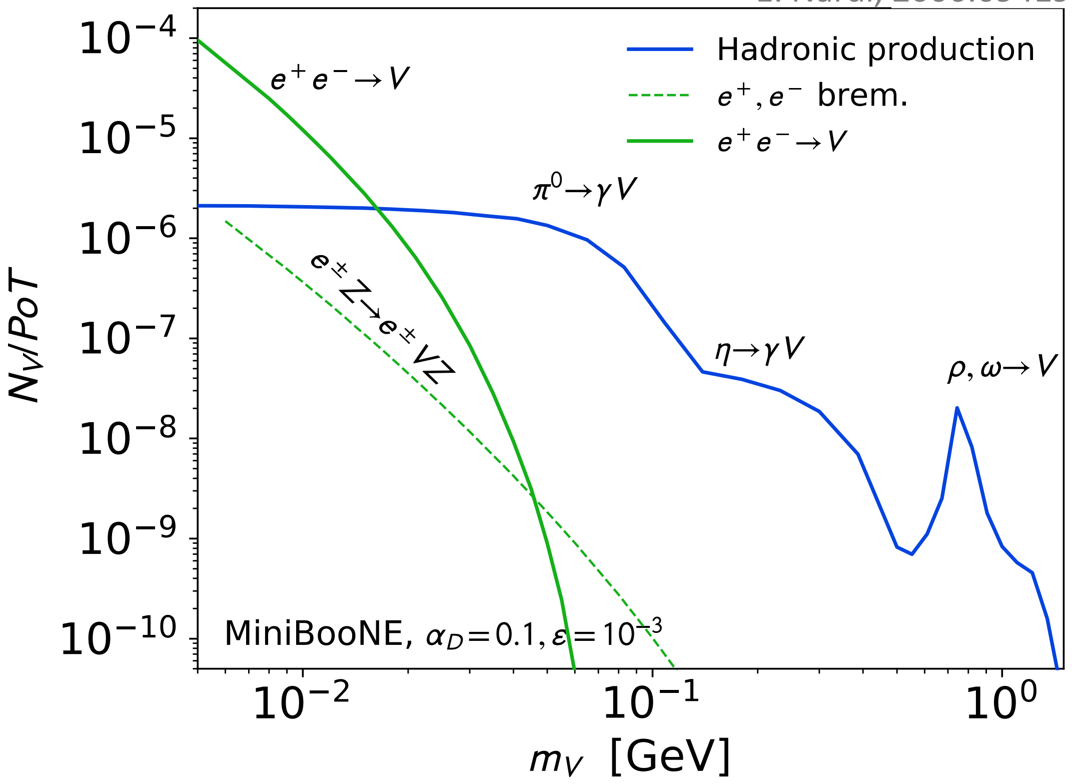
- Empirical distributions of light mesons (BMTP, Sanford-Wang, Burman-Smith)
- Analytical EM shower description, track length (Tsai, Rossi-Greisen/Lipari)
- Numerics: Pythia8, EPOS@LHC, QGS JETII, or GEANT4 , FLUKA (include secondaries)

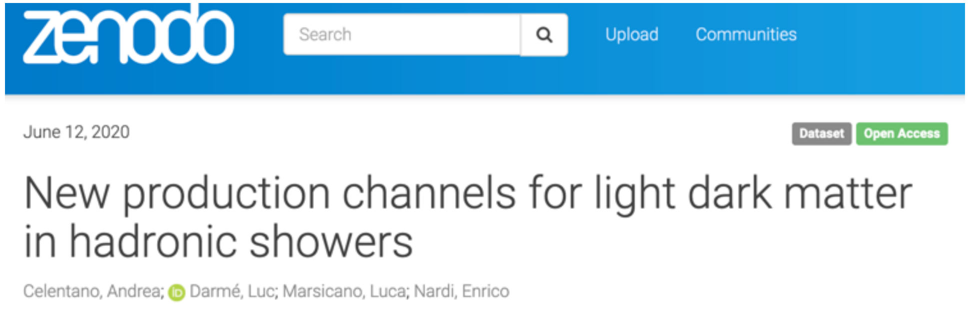
Bonesini et al., hep-ph/0101163
Sanford, Wang 1967
Burman, Smith 1989
Tsai, 1986
Rossi, Griesen 1941
Lipari, 0809.0190
Bierlich et al.
Pierog 2013
Ostapchenko 2007

Track length database: proton beam dump

- Proton beam dump are particularly challenging to simulate
  - Hadronic shower -> mesons distribution
  - EM- sub-showers
- GEANT4 simulation: secondary production dominate by almost 2 orders of magnitude for low dark photon mass
- Create and save $T_{\gamma,e^\pm}(\theta, E)$, $f_M(\theta_M, E_M)$ for a variety of proton beam dump experiments
  - Differential energy track lengths
  - Events dataset for $e^+/e^-/\pi^0$, for direct sampling

A. Celentano, LD, L. Marsicano, E. Nardi, 2006.09419





A. Celentano, LD, L. Marsicano, E. Nardi, 2006.09419

FIPs production in the lab

$e^{\pm}Z, pZ$ →

Mesons: f_{π^0}, f_η, f_K, …

EM processes: $T_{e^\pm}, T_\gamma$

→

e^+e^-, pp →

Flavoured mesons decay

$B \to K\,X, K \to \pi X, K \to inv$ or $D, B, J/\Psi \to \ell N$ etc …

→ Flavoured FIPs, Higgs portal and neutrinos portal

Light mesons decay

$\pi^0, \eta \to \gamma\, V$; $\rho, \omega \to V$ or $\pi^0 \to a$; $\pi^0, \eta \to \chi\chi$ etc …

EM-derived processes

$e^+e^- \to V\gamma, a\,\gamma$; $e\,N \to e\,N\,V$, etc …

→ Vector portal, ALP/fermion portal

- Mesons decays estimations
  - No automatic tool available (new light states: not possible to apply standard WET-based tools)

  → Analytical calculation required. BR usually estimated by standard techniques (χPT, Vector Meson Dominance, …) For VMD, see e.g. Fujiwara et al. (1985)

→ Limit on rare BR, $B \to K, K \to \pi$, $\pi \to inv.$, etc…

- EM-derived processes
  - For collider experiments: standard MC tools can be used (MG5_aMC@NLO, Alwall et al. 2014 CalcHEP, etc…) Belyaev et al. 2012
  - For beam dump → must include the track-lengths information, nucleus form factors…

→ Limits on mono-photon search @ BaBar/NA64/LEP

FIPs propagation and decay

FIPs production rates → *Propagation* →

Scattering signatures

$$\chi e \rightarrow \chi e \,;\, \chi N \rightarrow \chi N$$

Pure visible decay signatures

$$\mathrm{V}, \mathrm{a} \rightarrow \ell\ell, had. \,;\, \mathrm{a} \rightarrow \ell\ell, \gamma\gamma \;;\; S \rightarrow \ell\ell, had.$$
$$S \rightarrow V\, e^+ e^-$$

Semi-visible decay signatures

$$\chi_2 \rightarrow \chi_1 e^+ e^- \;;\, \mathrm{N} \rightarrow \nu\, \ell\ell, \nu\, \pi, etc..$$

→ Models of light dark matter

→ Dark photon, ALP, dark Higgs, Higgsed dark photon

→ Sterile neutrinos, inelastic DM …

- Requires MC tools: two public codes available, mostly for light dark matter
  - BdNMC (neutrino experiments mainly) deNiverville et al. 1609.01770
    - C++ code, include various empirical distribution for mesons, hard-coded dark photon production processes
    - Easily modifiable to include decay signatures and various experimental cuts
  - MadDump (Madgraph plugin) Buonocore et al. 1812.06771
    - Use the full MG machinery, can be thus used in variety of NP scenarios
    - Can be interfaced with track length databases
    - Mostly scattering signature currently → plan to include full decay search capability