Feebly-Interacting Particles and $(g-2)$ anomalies

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IP2I – CNRS

16/11/2021

Based mostly on 2012.11150, 2105.04540 and 2111.xxxx

This work has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626

Outline

Introduction: Feebly Interacting Particles for $(g-2)$

The MeV-regime: prospects of future resonant searches

The GeV regime: FIPs meddling in a_μ^{HVP}

Feebly-Interacting Particles and $(g-2)$

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

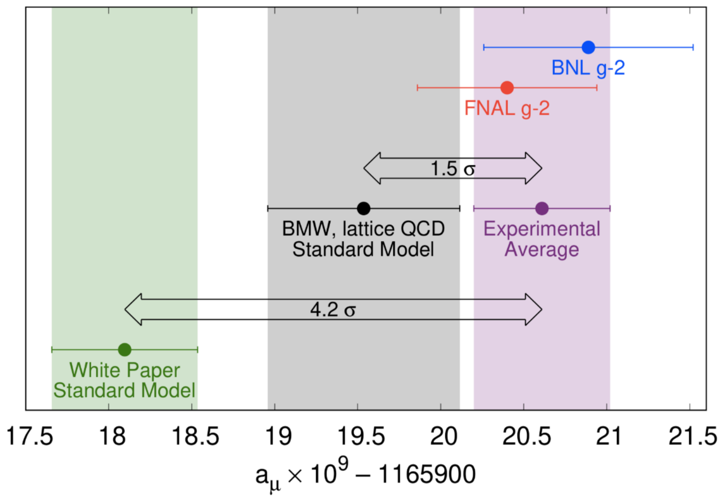
  → We focus in this talk on FIPs from MeV to tens of GeV range

  - Used often as a NP mechanism for $(g-2)_{\mu,e}$ Gninenko 2001, Baek 2001, Ma 2001… Brodsky 1967…
  - Part of simultaneous explanation of $B \to K$ and/or DM and $(g-2)$ A. Greljo 2021, Datta 2019, 2017, LD et al. 2020,2021 ..

- Anomalies in lepton magnetic moment are at a cross-road

Large anomaly in $a_\mu = (g-2)_\mu$

w.r.t data-driven SM theory estimates



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

Confused situation for $a_e = (g-2)_e$

on the exp. side

$$\Delta a_e \equiv a_e^{\rm SM} - a_e = +(4.8 \pm 3.0) \cdot 10^{-13} \qquad ({\rm LKB-2020})$$

$$\Delta a_e \equiv a_e^{\rm SM} - a_e = -(8.7 \pm 3.6) \cdot 10^{-13} \qquad ({\rm Berkeley\text{-}2018})$$

More tension between both exp. measurements than with the SM prediction …

Two FIP examples …

- An axion-like particle (ALP) a,

$$\mathcal{L} \subset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \frac{1}{4}g_{a\gamma}a\boxed{F_{\mu\nu}\tilde{F}^{\mu\nu}} + \sum_{f=\ell,q} g_{af}m_f\boxed{(a\,\bar{f}\gamma^5 f)}$$

→ We then "hide" the ALP via a coupling to a dark current

$$\mathcal{L} \supset \frac{g_{a\chi}}{2}(\partial_\mu a)\mathcal{J}^\mu_{5,D}$$

→ Contains FIP/dark sector interaction, can be large!

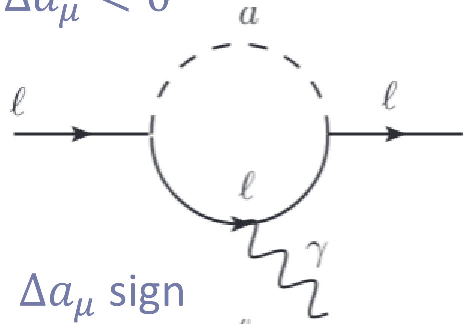
- Same procedure can be applied to a light vector FIP V^μ

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}M_V^2\,V_\mu V^\mu + \frac{\epsilon}{2}V_{\mu\nu}\boxed{F^{\mu\nu}} + \sum_{f=\ell,q}\boxed{g_{Vf}V_\mu\,\bar{f}\,\gamma^\mu f}$$

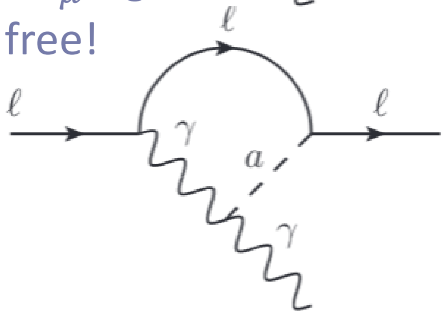
+ a dark current coupling

→ Covers standard cases: dark photon, $L_\mu - L_\tau$, etc…

$\Delta a_\mu < 0$

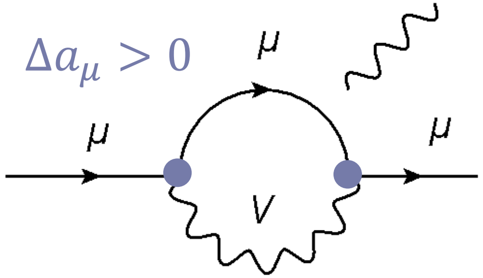


Δa_μ sign free!



+ light-by-light and 2-loops lepton loop contributions

$\Delta a_\mu > 0$

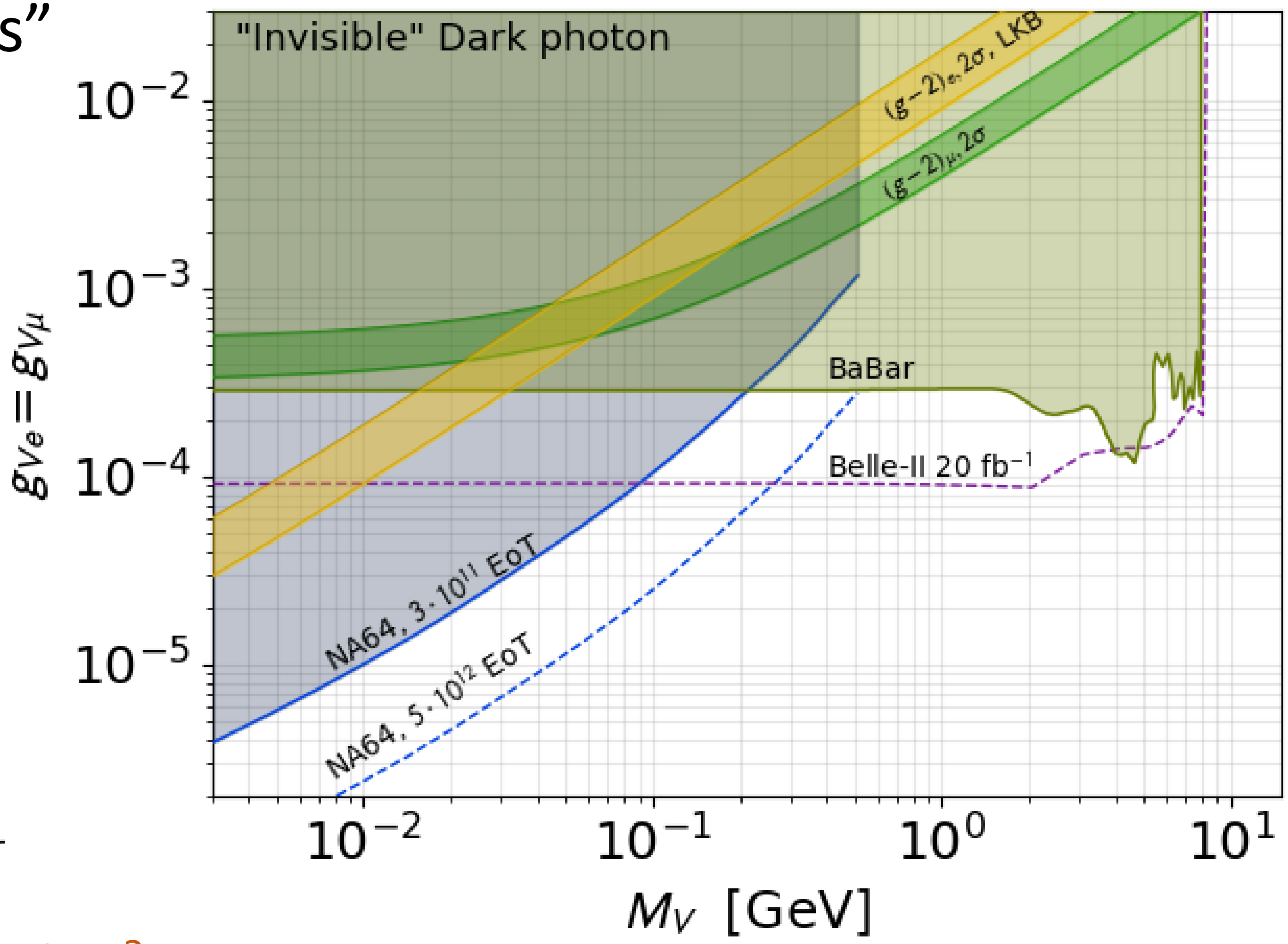


Going resonant on « radiative » electron-FIP interactions

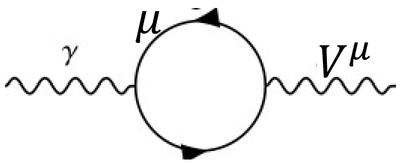
Vector FIP limits: the universal case

- Previous experimental programs covered Δa_μ and Δa_e in "universal scenarios"
- However these limits are electron-driven
  - →For $(g-2)_\mu$ only the muon coupling is really required
- Radiative corrections can re-introduce e^- coupling
  - E.g $L_\mu - L_\tau$: kinetic mixing typically arises from SM fermions loop

Adapted from LD, F. Giacchino, E. Nardi, M. Raggi, 2012.07894



$$\varepsilon \sim \frac{e\, g_{V\ell}}{6\pi^2}\, log$$

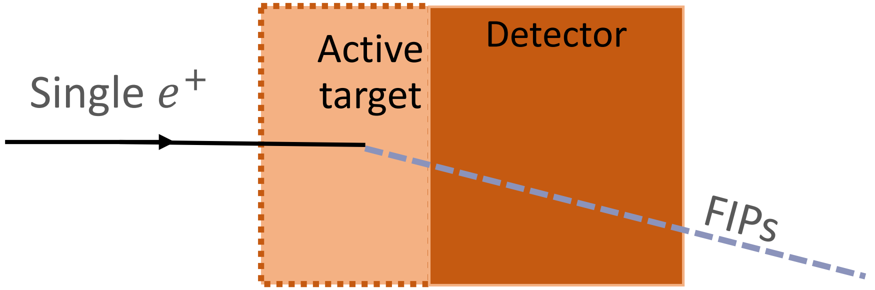


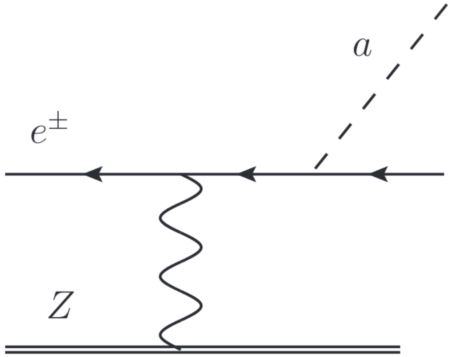
→ Can we probe such suppressed couplings at accelerators ?

Resonant production for light (bosonic) FIPs

- In beam dumps, the most effective production mechanism is the resonant process $e^+e^- \rightarrow FIP$

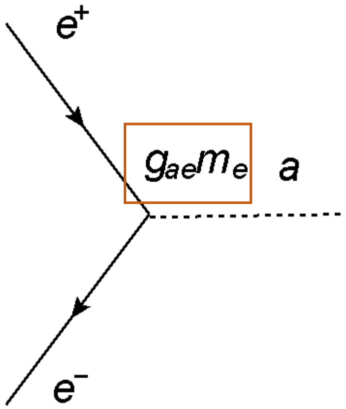
  → Use e^+ beam with annihilation on the target's e^-





Bremsstrahlung process

$$\sigma_{ae} \propto \alpha_{\rm em}^2 g_{ae}^2 \frac{m_e^2}{m_a^2}$$



Resonant process

→Cross-section x100-1000 times larger

→Due to low CoM $\sqrt{s}$, only low masses accessible

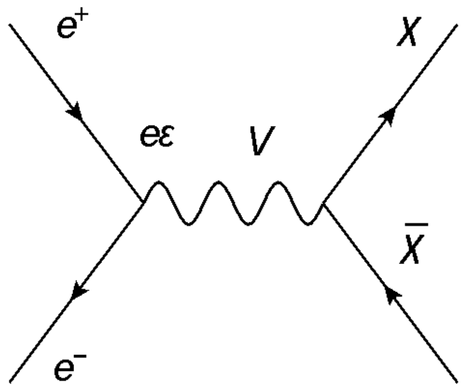
$$\sigma_{res} \sim \pi g_{ae}^2 m_e \delta(E_+ - E_{res})$$

- Enormous gain in cross-section, to the cost of having to match the precise resonant energy

$$E_{\rm res} \equiv \frac{m_a^2}{2m_e}$$

Resonant production and production rates

How to get to the exact energy?



- Study models with large invisible width Γ_V^{inv}
  → typical for dark photon with light dark matter where it decays invisibly with large rate.

- Vary the beam energy directly when possible

See e.g. 1802.04756

See e.g. 1802.03794, 2105.04540

- Use energy loss in the target to "scan" naturally various positron energies

  → Charged particles in matter undergo "straggling", bremsstrahlung, etc …

  → Builds a secondary population of lower energy particles as part of the E-M shower initialisation

  → Distinguishing the signal from background typically implies a cut to enforce e.g $E_{e^+} > E_{beam}/2$. Precise cut to be determined experimentally

Strong constraint on "secondary" electron coupling

- Showing production-only, 3-events lines, PRELIMINARY

  → POKER proposal, SPS-based 100, 50, 25, 2 GeV e^+beam

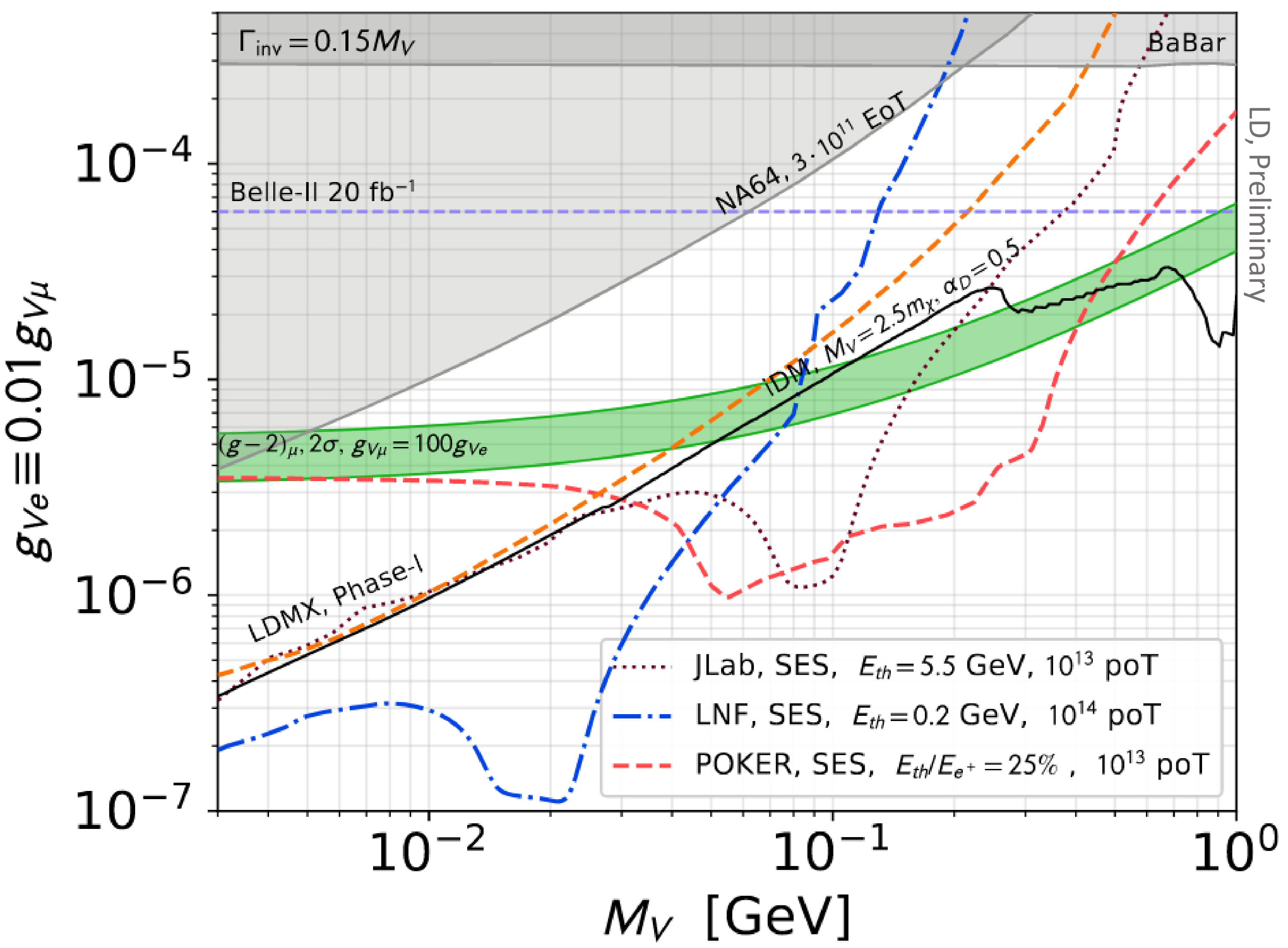
  → JLab, 11 GeV e^+ beam

  → LNF, 0.5 GeV e^+ beam

- Several energy beams needed to cover parameter space
  - Significant coverage of radiatively-generated electron coupling!

    → Also covers light dark matter solutions, works for e.g. $L_\mu - L_\tau$

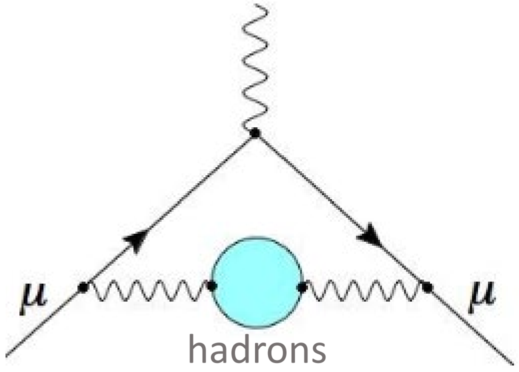
3-events line: production only



GeV-scale FIPs meddling with a_μ^{HVP}

LD, Grilli di Cortona, Nardi, Preliminary, 2111.xxxx

Discrepancies in the SM estimate a_μ^{HVP}

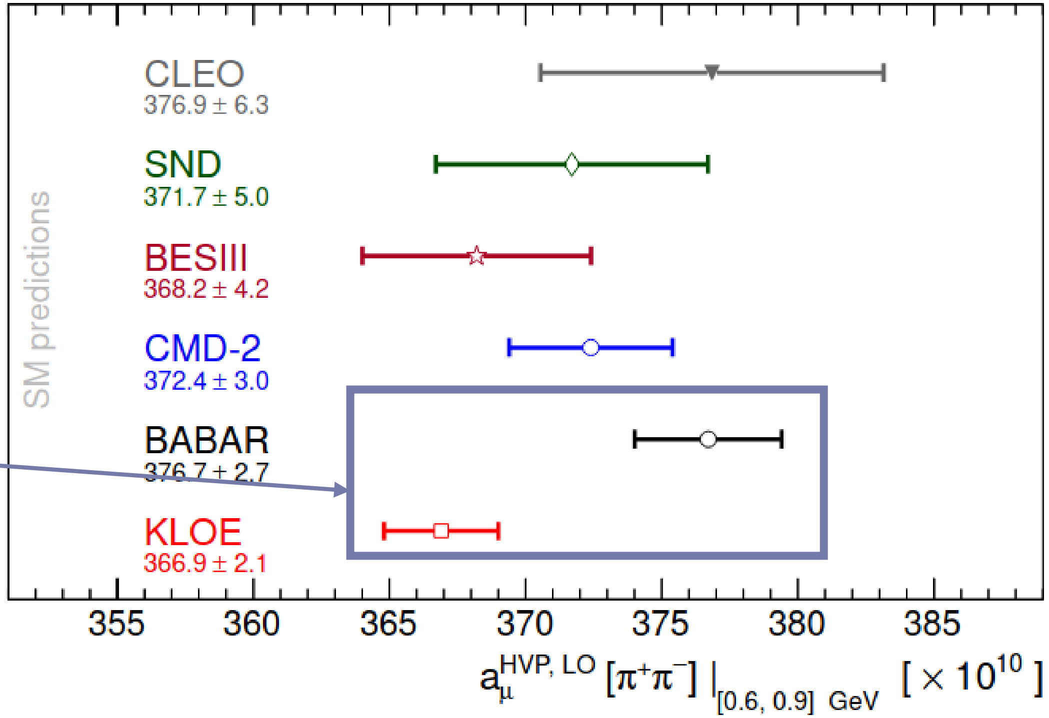


- We focus on a key ingredient of the data-driven approach: Hadronic Vacuum Polarisation component

$$a_\mu^{\text{LO,HVP}} = 693.1 \pm 4.0 \cdot 10^{-10}$$

- Currently three anomalies!
  - Latest lattice result do not agree with data-driven approach
  - Neither agree with the experimental value
  - Within the data driven, $\sim 3\sigma$ disagreement between the two main exp. contributions

Muon g-2 Theory Initiative, 2006.04822



..And with the τ hadronic decay data

Shifting a_μ^{HVP} from luminosity measurements

- Use the optical theorem to deal with the loop

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

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

- The absolute cross-section is required → so the luminosity estimate is critical
  - The luminosities in KLOE and BaBar are measured via Bhabha scattering $e^+e^- \to e^+e^-$ at large angles
  - We can mimick efficiently this process via $e^+e^- \to V \to e^+e^-$. For instance, let's assume a FIP near the KLOE CoM energy $M_V \sim \sqrt{s_{KLOE}} \sim M_\phi$

$\sigma^{True}_{\text{"}Bhabha\text{"}} > \sigma^{SM}_{Bhabha}$ ➡ $L^{True}_{KLOE} < L^{SM}_{KLOE}$ ➡ $\sigma^{True}_{had} > \sigma^{SM}_{had}$

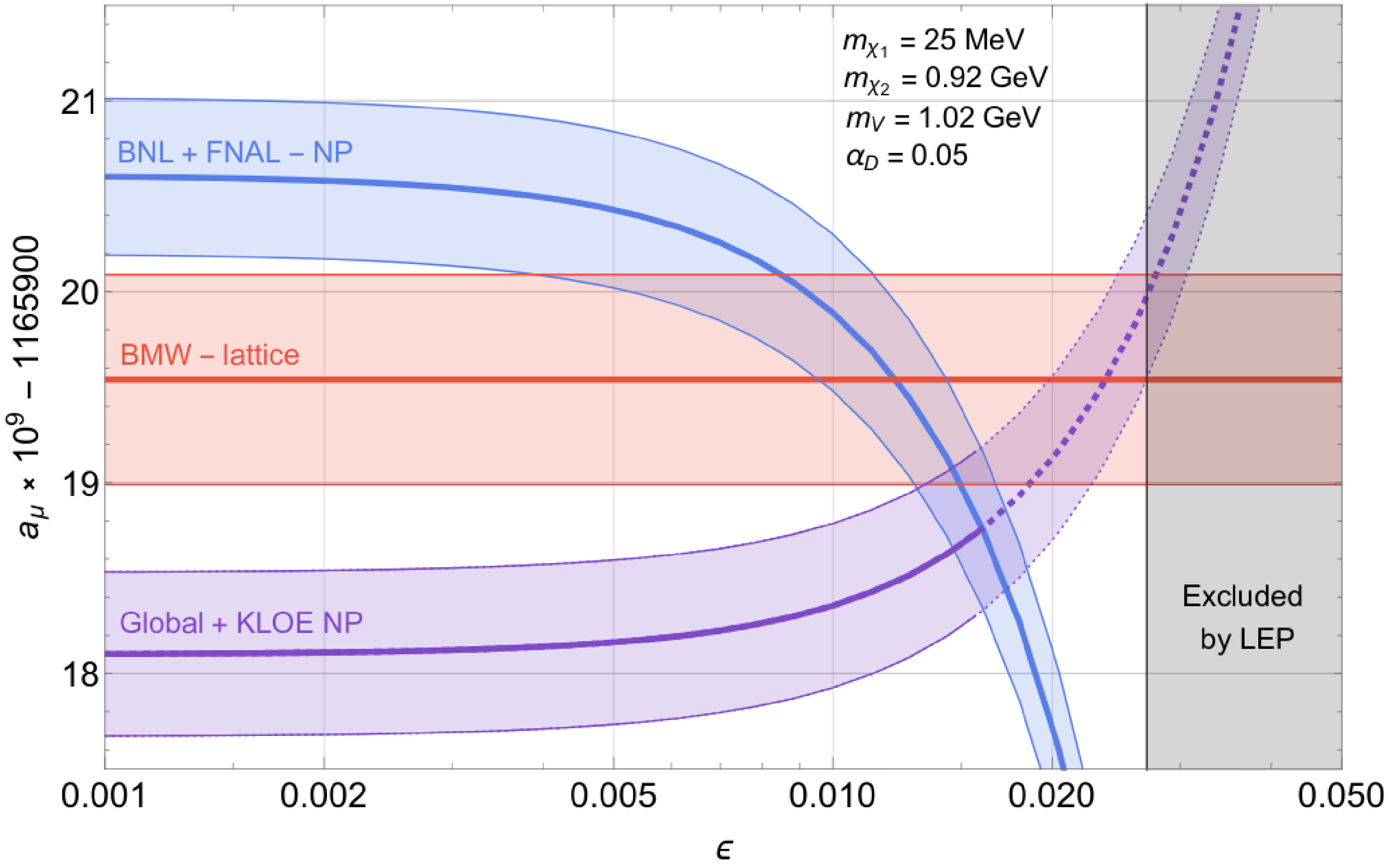
KLOE reported a given number of Bhabha-like events $N \propto \sigma \times L_{KLOE}$

If the luminosity is smaller, then larger hadronic CS $N \propto \sigma \times L_{KLOE}$

Requires tuning, but actually works!

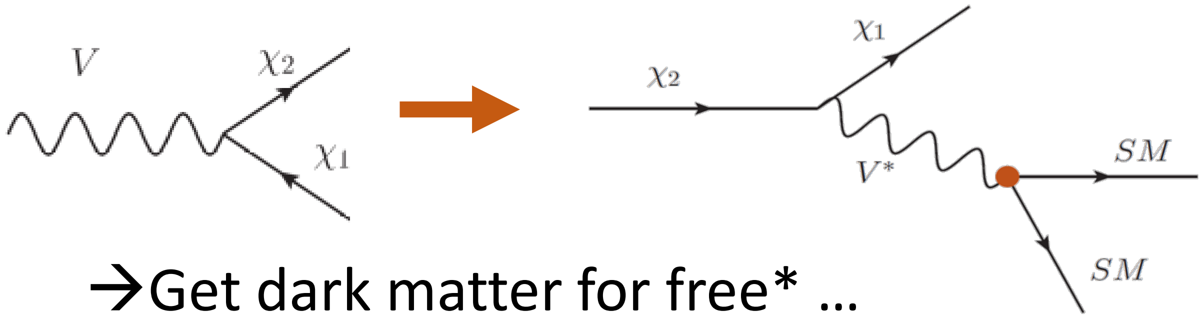
- Resonant FIP production at KLOE is required
  - → Around 2/3 of Δa_μ from NP loop and 1/3 from this effect
- Solve in one go all tensions in Δa_μ-related observables !
  - → Lattice vs Data-driven, theory vs experiment, KLOE vs BaBar
- Large kinetic mixing required however

LD, Grilli di Cortona, Nardi, Preliminary, 2111.xxxx



Stealthy dark photons

- Use « inelastic dark matter scenario » to avoid bounds on dark photons



→Get dark matter for free* …

- Semi-visible signatures are difficult experimental target. E.g in BaBar:

  → Visible type searches do not include missing energy

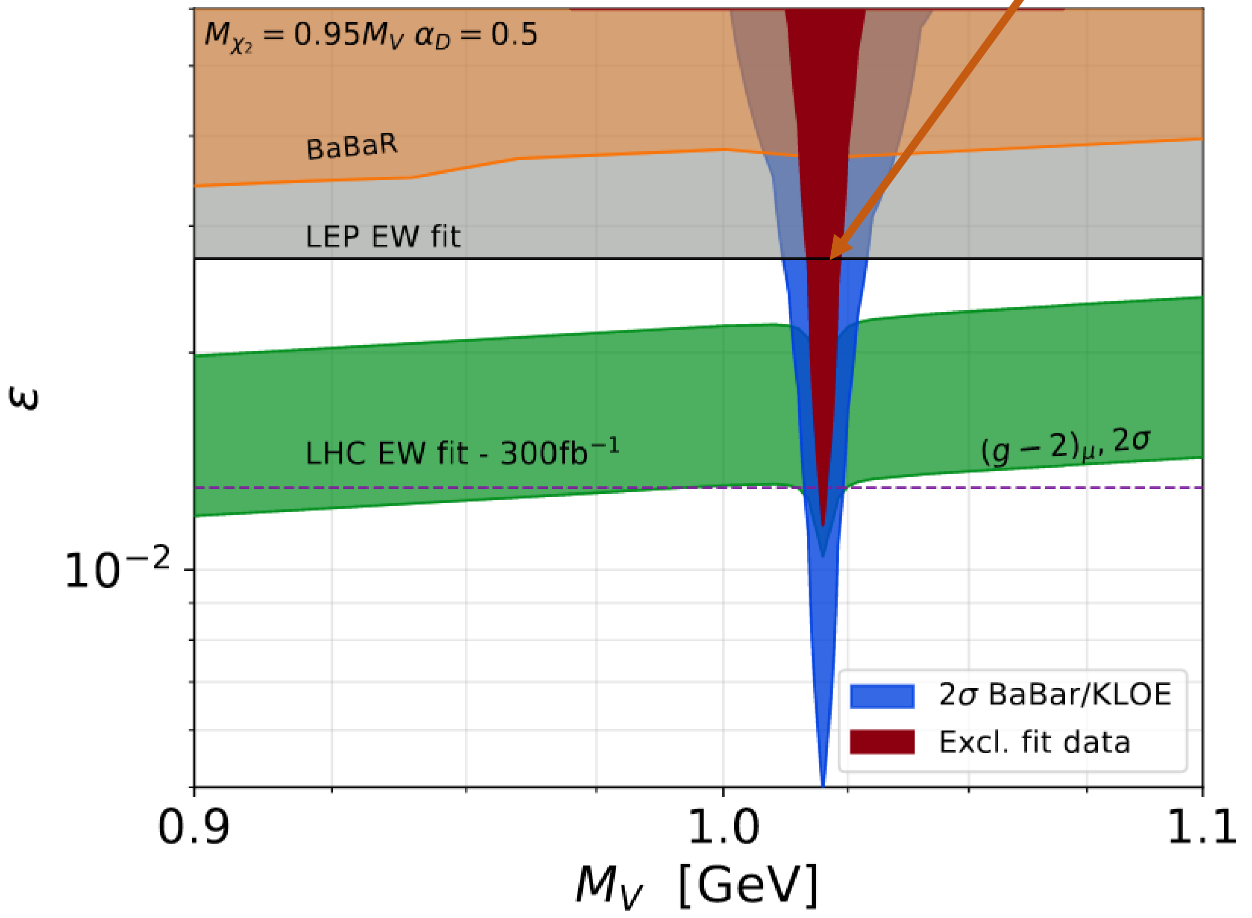
  → Invisible decay/mono-photon cut on the e^+e^- decay products

- Target for Belle-II !

Mohlabeng 2019,Duer 2019, Duer 2020, Laura Zani's talk

Tuning required as expected from resonant production at KLOE

LD, Grilli di Cortona, Nardi, Preliminary, 2111.xxxx



*Via dark Higgs secluded annihilation, the dark Higgs is required in this scenario in any case

Conclusion

Conclusion

- Flavoured FIPs have been long used to fit various “precision anomalies”

  → Flavour-dependent FIPs are still a viable solutions to provide a fit $(g-2)_{e/\mu}$ experimental results and provide additional interesting effects

- Next generation of precision beam dump experiments could be sensitive to suppressed radiatively-generated e^-/e^+ couplings from “standard” $(g-2)_\mu$ solutions

  → Promising resonant-based strategies

- For FIPs in the GeV mass range, more exotic effects on $(g-2)_\mu$ can arise

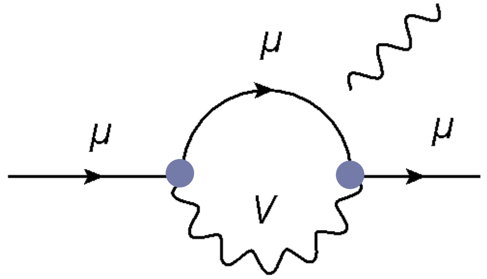
  → A FIP around the KLOE CoM energy could solve in one go all tensions in Δa_μ-related observables !

Backup

Fitting the anomalies, couplings to muons

- At small FIP masses, $(g-2)_\mu$ anomaly typically requires small couplings to muons to avoid "overshooting"

$(g-2)_\mu$, vector



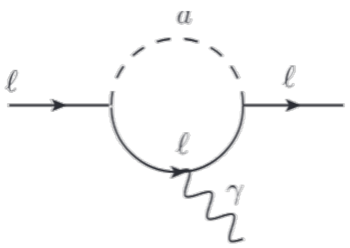
$\Delta a_\mu > 0$ for $g_{V\mu}$, $\Delta a_\mu < 0$ for $g_{A\mu}$

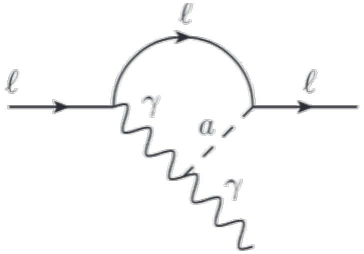
$$\sqrt{g_{V\mu}^2 - 5\, g_{A\mu}^2} \sim 0.05 \left(\frac{1\,\mathrm{GeV}}{M_V}\right)$$

around the GeV

Saturation when $m_V \sim m_\mu$

$(g-2)_\mu$, ALP





+ light-by-light and 2-loops lepton loop contributions

$\Delta a_\mu < 0$

Δa_μ sign free!

Going via the Barr-Zee diagram we have for instance

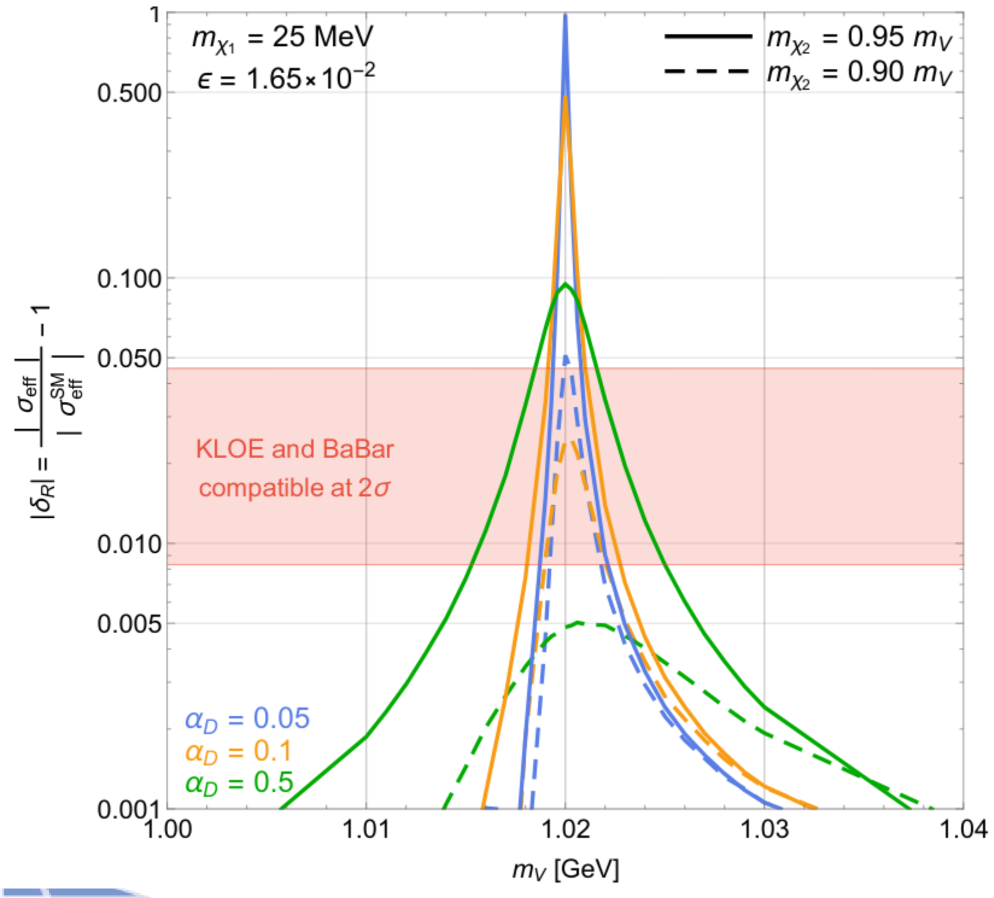
For muon : $g_{a\gamma} g_{a\mu} \sim -(0.001)^2$ GeV^{-2}

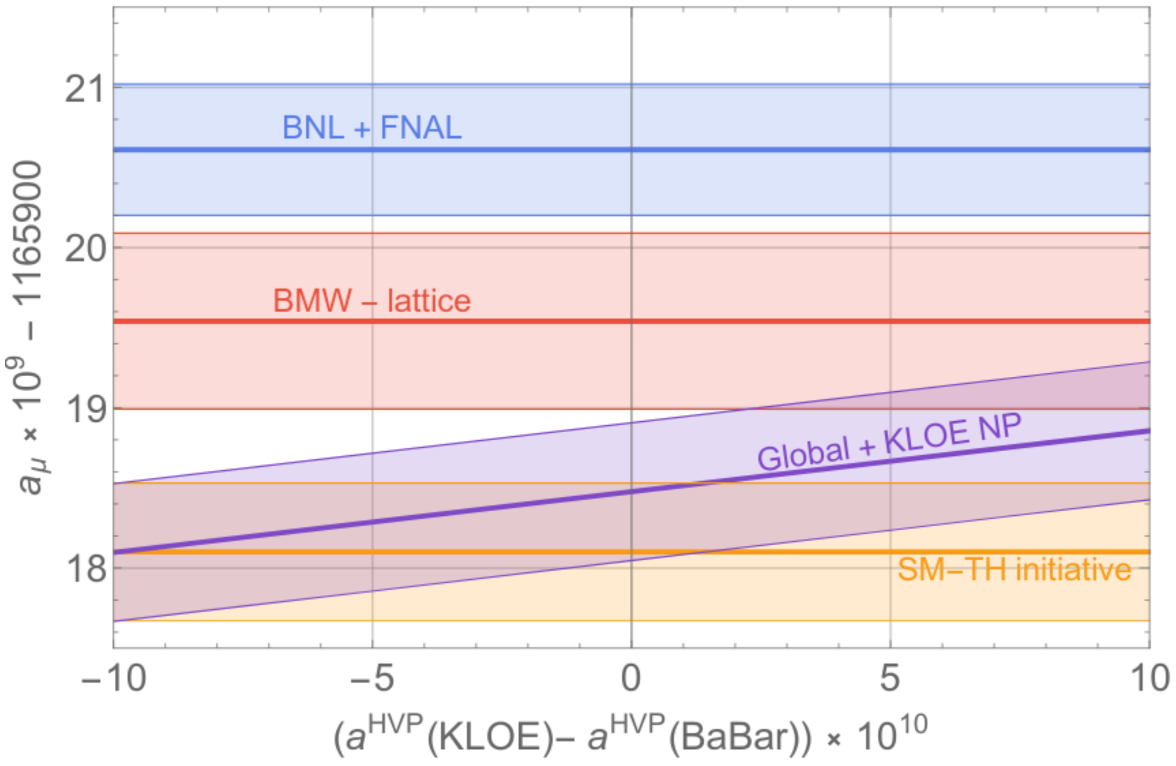
For electron :$g_{a\gamma} g_{ae} \sim \pm(0.0025)^2$ GeV^{-2}

Illustrating the resonance

- No effect outside of the resonance: safe for other experiments

LD, Grilli di Cortona, Nardi, Preliminary, 2111.xxxx





- Data-driven estimate quite robust again a change in a single experiment

Portal interactions

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

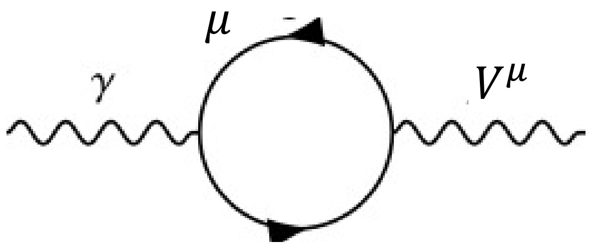
→ A neutral particle, must be coupled to a neutral “current” in the SM

	SM operator	FIPs / dark sector	examples …
Scalar portal	$\|H\|^2 \quad (d=2)\,, \longleftrightarrow$	$\|S\|^2$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,, \longleftrightarrow$	$F'^{\mu\nu}$	Dark photon
Neutrino portal	$LH \quad (d=5/2) \longleftrightarrow$	N	HNL
Axion portal / fermion portal	$\bar{f}_i\,\Gamma^\mu f_j \quad (d=3)$	$\partial_\mu a\,, V_\mu$	ALP/L_μ- L_τ…
		$\Psi\Gamma_\mu\Psi$	Dark fermions

Focus mostly on these two portals in this talk.

Couplings to photons and electrons

- Even for models focusing on $(g-2)_\mu$, neglecting couplings to electrons/photon is not always well-grounded
  → Radiative corrections typically re-introduce the other couplings
- For a vector FIP, kinetic mixing typically arises back from SM fermions loop
  → Barring tuning with new UV states, kinetic mixing reappears with a loop factor



Holdom 1985 $$\varepsilon \sim \frac{e\, g_{V\ell}}{6\pi^2}\, log$$

- For an ALP, couplings are re-generated following $g_{a\mu} \Longrightarrow g_{a\gamma} \Longrightarrow g_{ae}$
  → And of course, electron couplings are also required for Δa_e …

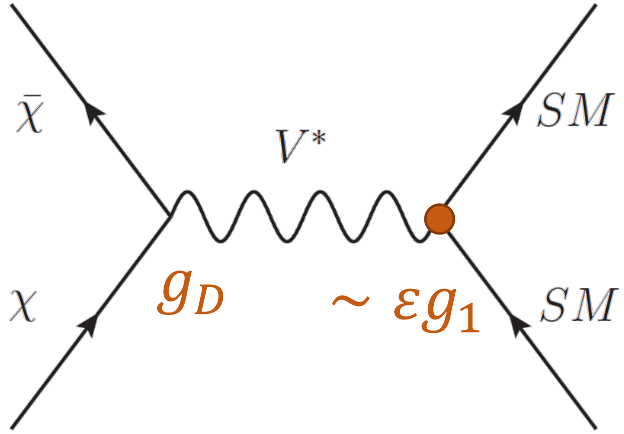
The key points is that exp. constraints on photon & electrons are very strong…

Couplings to a dark sector

- Interest in FIPs also driven by building models of thermal sub-GeV DM

- Standard example: a vector portal with a Majorana fermion

  → Relic density: sub-GeV DM requires $\varepsilon \sim 10^{-3}$ suppression



- Most FIP models can be embedded in a light dark matter setup (of course with various level of complexity …)
  - ALP model with resonant annihilation e.g. Dolan et al. 1709.00009
  - most light vector FIP models assuming small kinetic mixing

Altogether an extremely rich literature of new “mechanisms” to obtain the relic density (Forbidden DM, Secluded DM, Selfish DM, Cannibal DM, etc …)

→ Motivate including “invisible” decay channels for the FIP

Dark photon/ALP production in e^+/e^- machines

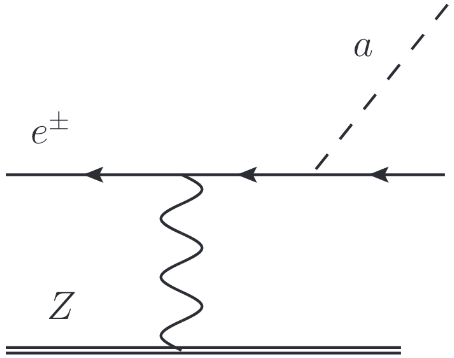
We focus primarily on the couplings FIP interactions with e and γ

→ NB: Interesting proposals to use muon beam directly not included (eg. NA64μ)

→ Electron-only machine mostly rely on Bremsstrahlung/Primakoff from secondary photon

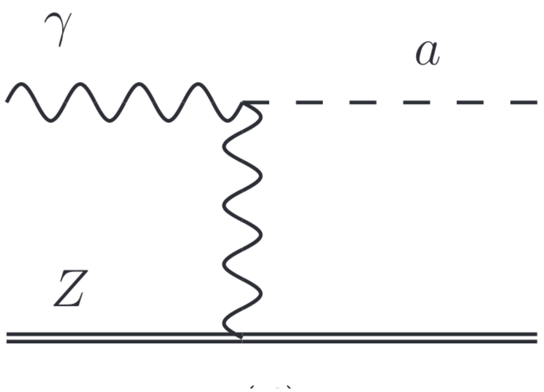
→ Positron machine have more channels (annihilation on beam target's electrons)

All lepton machines



Bremsstrahlung

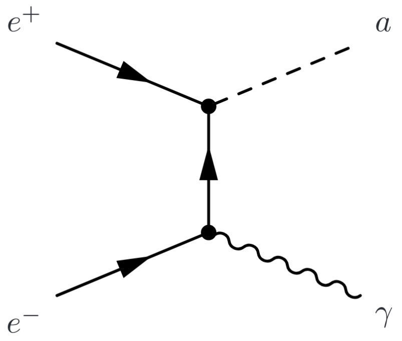
$$\sigma_{ae} \propto \alpha_{\rm em}^2 g_{ae}^2 \frac{m_e^2}{m_a^2}$$



Primakoff (ALP)

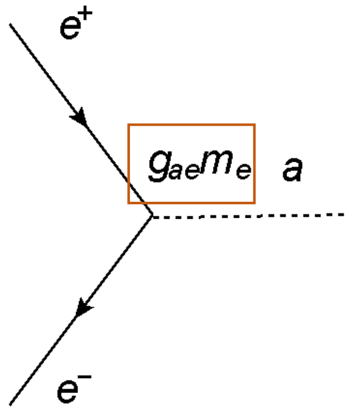
$$\sigma_{a\gamma} \propto \alpha_{\rm em} g_{a\gamma}^2$$

Positron beam dump or e^+e^- colliders



Associated/mono-γ

$$\sigma_{ae} \sim \alpha_{\rm em} g_{ae}^2 \frac{m_e^2}{2s} \log\left(\frac{s}{m_e^2}\right)$$



etc...

Resonant

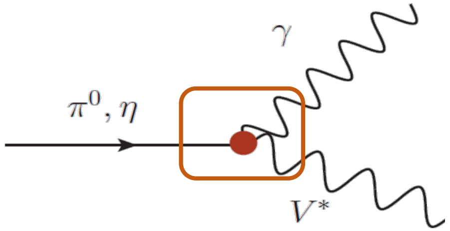
$$\sigma_{res} \sim \pi g_{ae}^2 m_e \delta(E_+ - E_{res})$$

Detection strategies: two mass ranges

Beam dumps: lower CoM and smaller masses

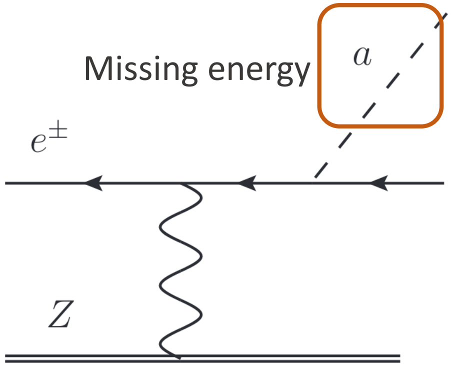
- Intensity beam dumps: typically p machines (beam neutrinos exp, SHiP).

  → Visible FIP signature in shielded detector ”far” away required



- Precision beam dumps: typically e^+ or e^- machine (NA64, PADME, LDMX, etc…). Search for large missing energy

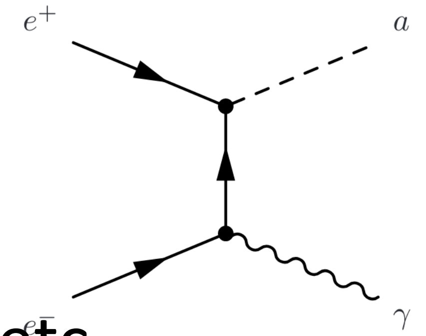
  → Limited by detector response (~1 particle per 10 ns), near zero background



Less sensitive but larger masses

- e^+e^- colliders (LEP, BaBaR, Belle-II …): Mono-photon search or visible decay

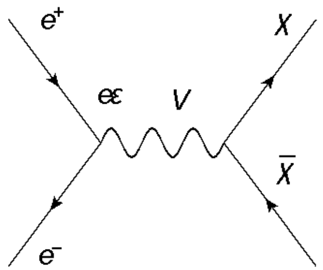
  → Large luminosity, background control critical



- Complementary strategies: LLP@LHC, rare meson decay, etc…

Resonant production and production rates

- How to get to the exact energy?
  - Study models with large invisible width Γ_V^{inv} → typical for dark photon with light dark matter

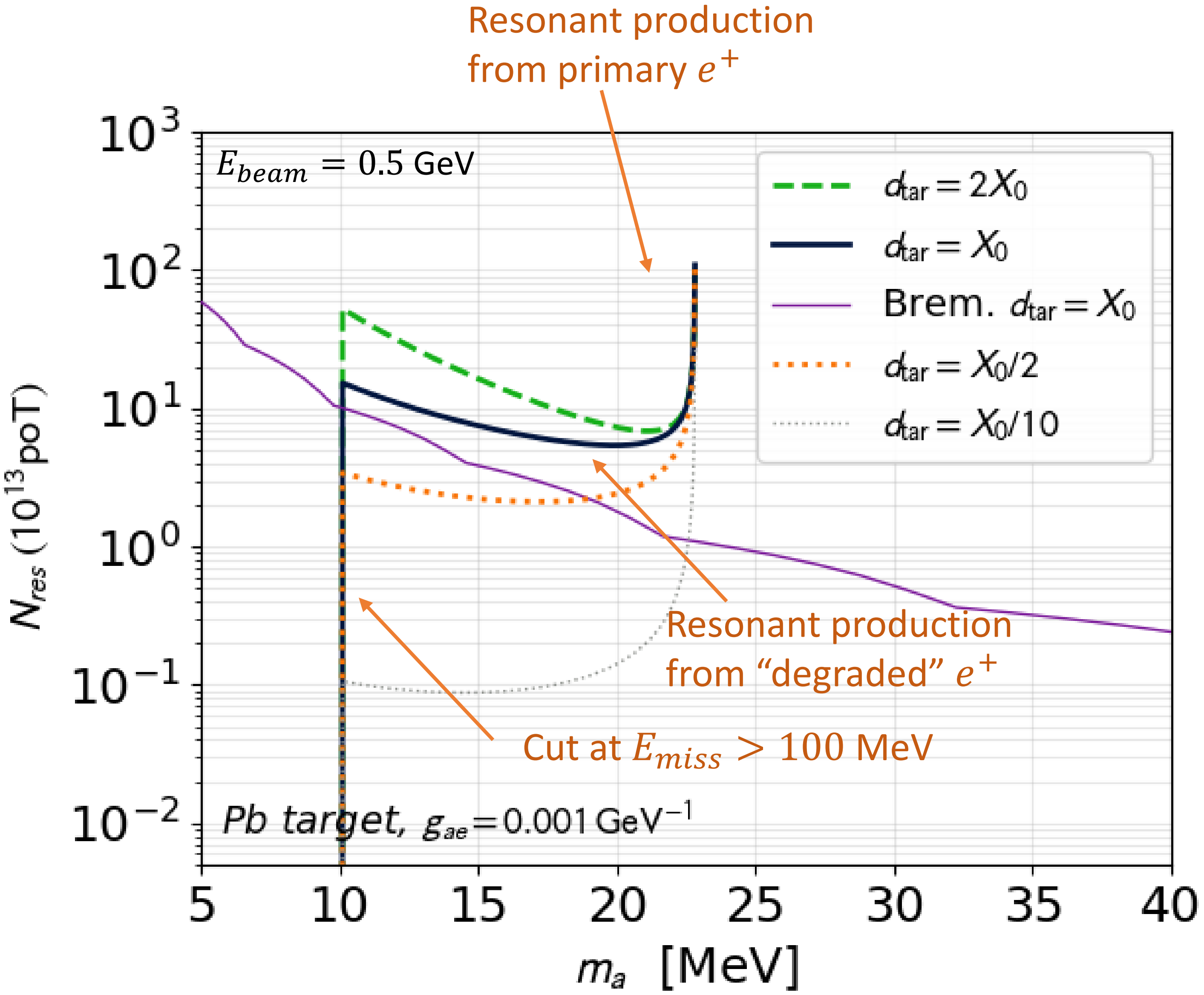


- Vary the beam energy (+ radiative return)

  See e.g. 1802.04756

- Use energy loss in the target to "scan" naturally various positron energies

  See e.g. 1802.03794, 2105.04540



Mass dependence

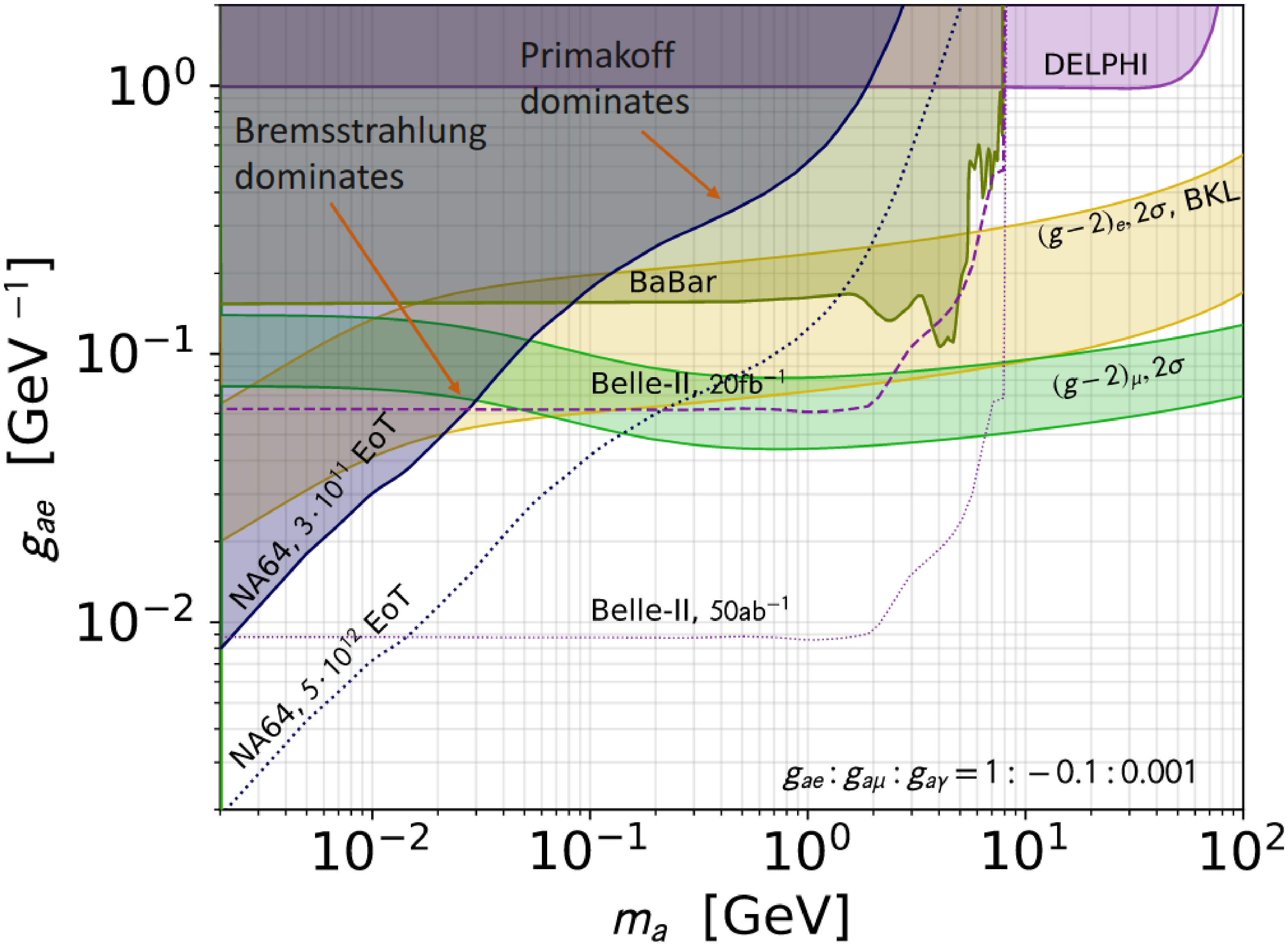
- We fix the ratio between the various couplings, e.g.

$$g_{ae} = 10^3 g_{a\gamma} = -10\ g_{a\mu}$$

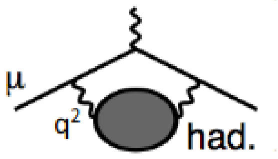
- The FIP mass determines which coupling dominates the prod. rates

→ Has a strong impact on the bounds (e.g NA64)

Adapted from LD, F. Giacchino, E. Nardi, M. Raggi, 2012.07894

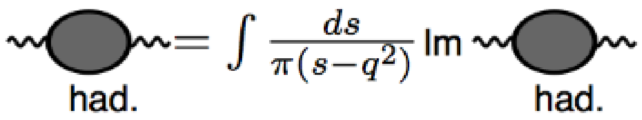


a_μ^{HVP} : Basic principles of dispersive method



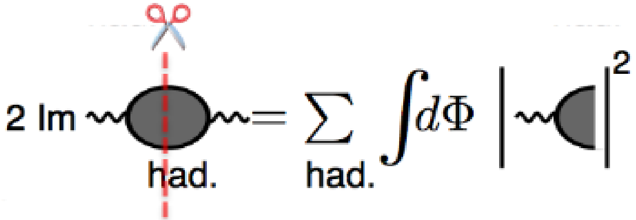
One-loop diagram with hadronic blob =

integral over q^2 of virtual photon, 1 HVP insertion



Causality ➠ analyticity ➠ dispersion integral:

obtain HVP from its imaginary part only



Unitarity ➠ Optical Theorem:

imaginary part (`cut diagram') =

sum over |cut diagram|², i.e.

∝ sum over all total hadronic cross sections

$$\boxed{a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)}$$

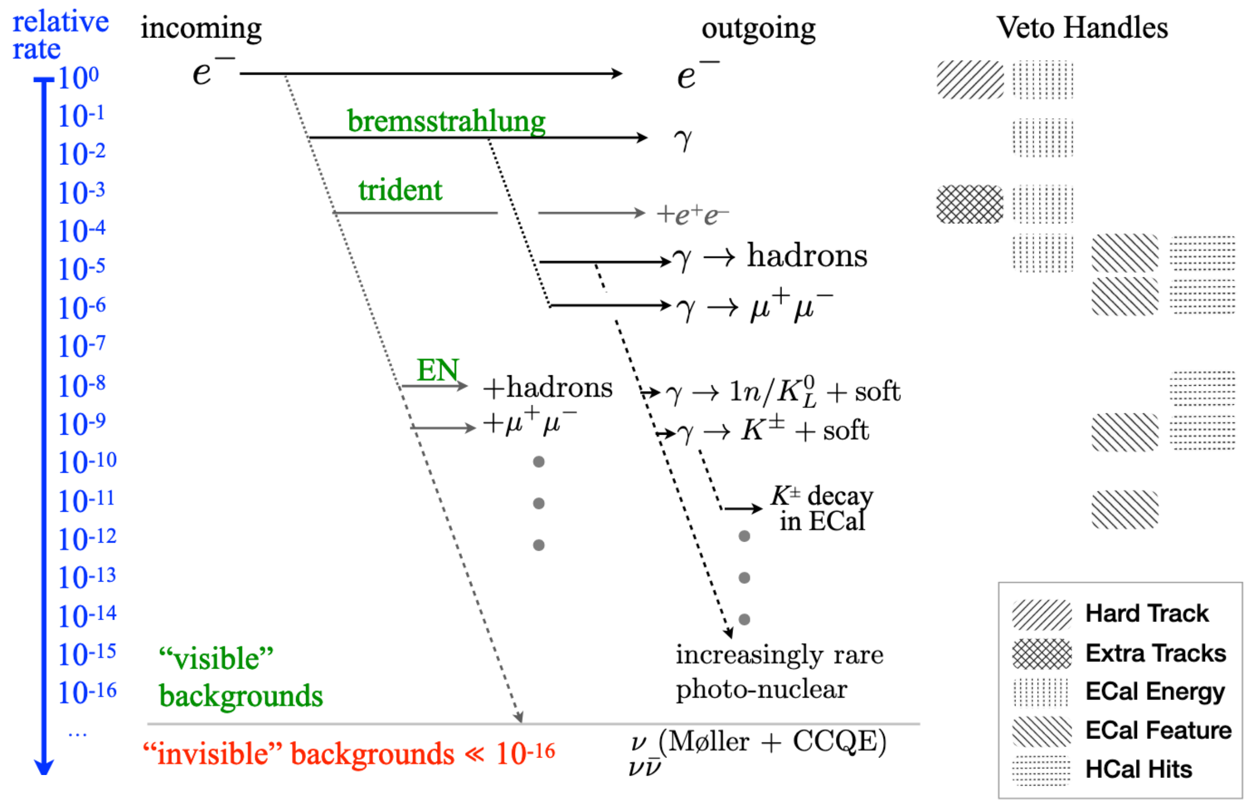
- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$
  $\Longrightarrow$ Lower energies more important
  $\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{had,LO}}$

From Thomas Teubner talk at g-2 days 2021

- Total hadronic cross section σ_{had} from >100 data sets for e^+e^- ➞ hadrons in >35 final states
- Uncertainty of a_μ^{HVP} prediction from statistical & systematic uncertainties of input data
- Pert. QCD used only at large s, **no modelling** of $\sigma_{had}(s)$ **required**, direct data integration

Example of background processes, estimated by LDMX

LDMX collaboration 1808.05219



LDMX collaboration 1808.05219

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1