Laura Zani: laura.zani@roma3.infn.it

Roma Tre – Seminar cycle for PhD

DARK SECTORS
AND WHERE TO FIND THEM

Today's **Highlights**

- Why dark matter?
- Why dark sectors?
- How to search for dark sectors?
  - Detection techniques
  - Focus on searches at e^+e^- colliders (B-factories)
    - Examples of actual searches

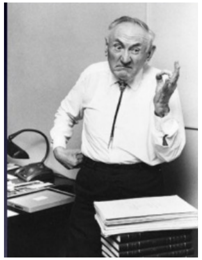
DISCLAIMER: I am not a theorist...

Evidences for dark matter

- Many **astrophysics** and **cosmological observations** provide evidences for Dark Matter (DM) existence:

Galaxy rotation curves

F.Zwicky, 1933



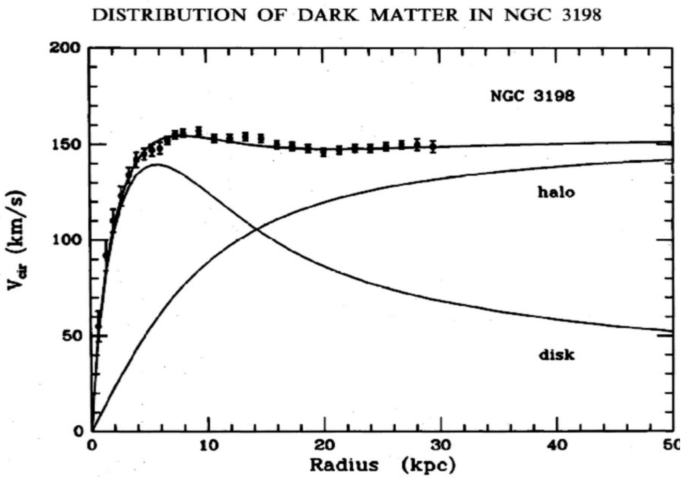
Examined Coma cluster galaxy with Virial Theorem:

$2E_{kine} = - U$

$$<v(r)^2>=GM(r)/r$$

M(r) ~400x luminous matter

V.Rubin, 1970s



Flat rotational curves:

$v(r) = const$

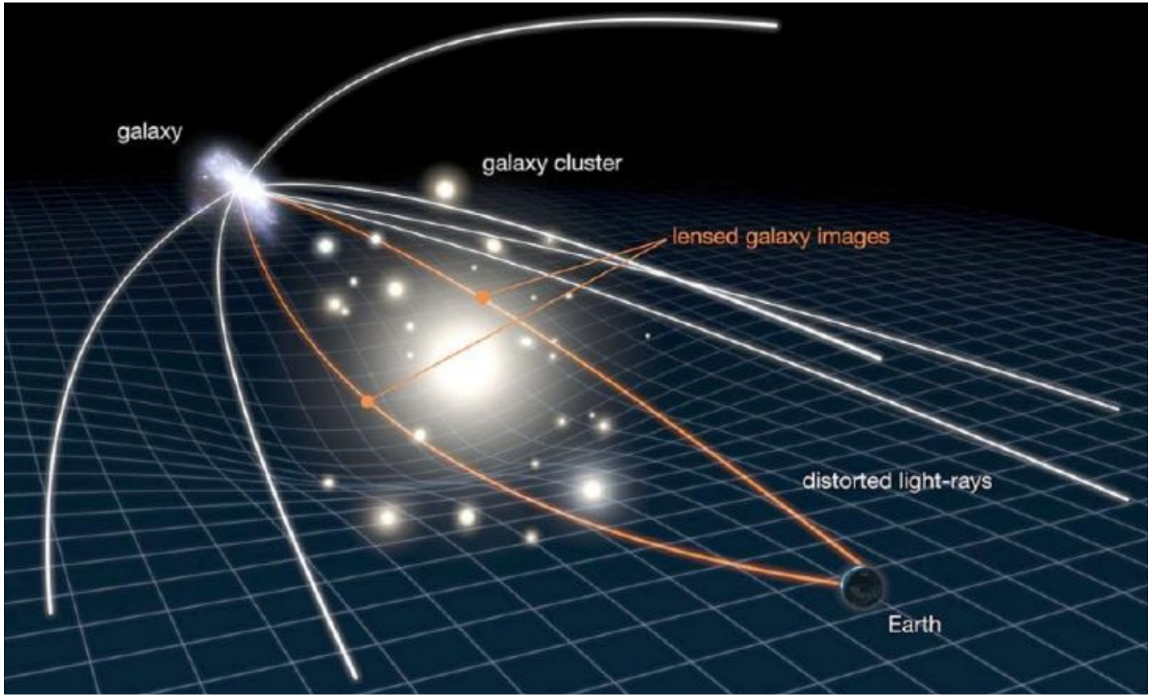
→ mass distribution linearly growing with r (assuming $\rho(r)=1/r^2$)

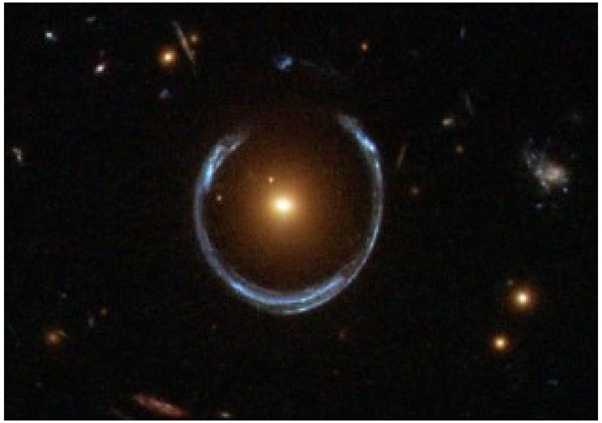
→ DM gravitates

Evidences for dark matter (II)

- Many **astrophysics** and **cosmological observations** provide evidences for Dark Matter (DM) existence:

Gravitational Lensing



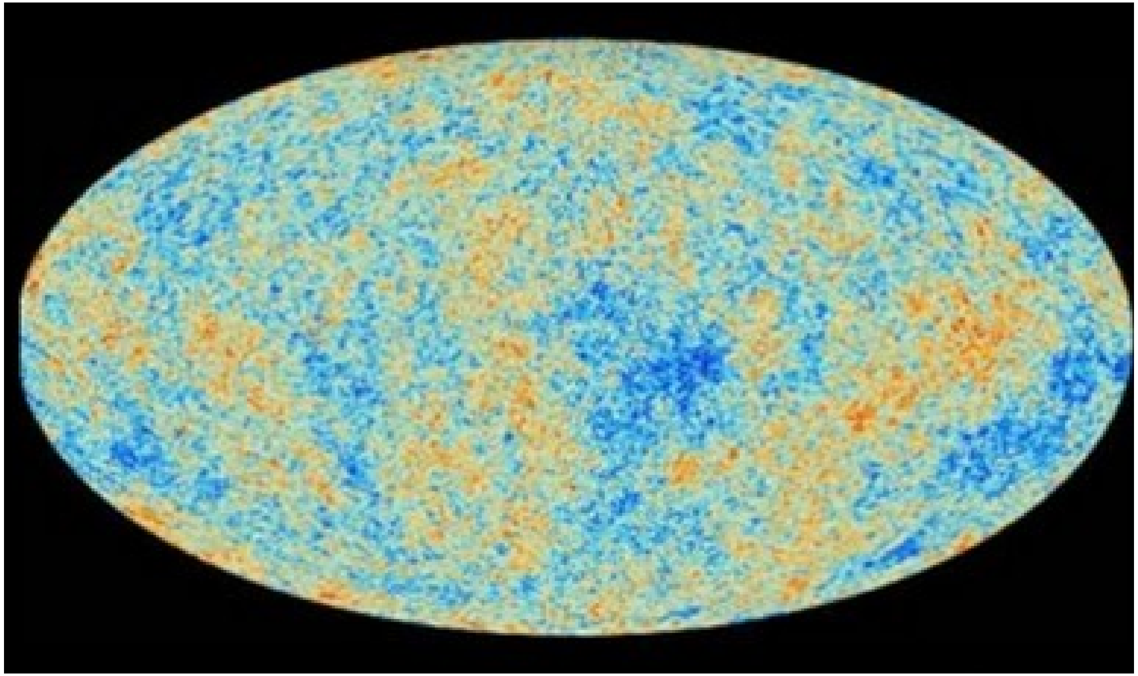


→ it's dark (doesn't interact electromagnetically)

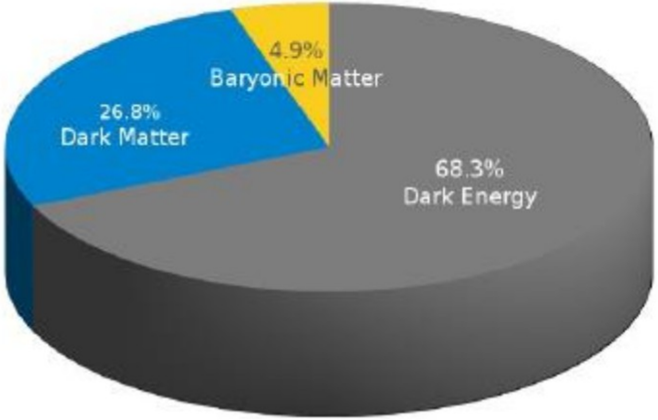
Evidences for dark matter (III)

- Many **astrophysics** and **cosmological observations** provide evidences for Dark Matter (DM) existence:

Cosmic Microwave Background anisotropies (from Planck satellite data)

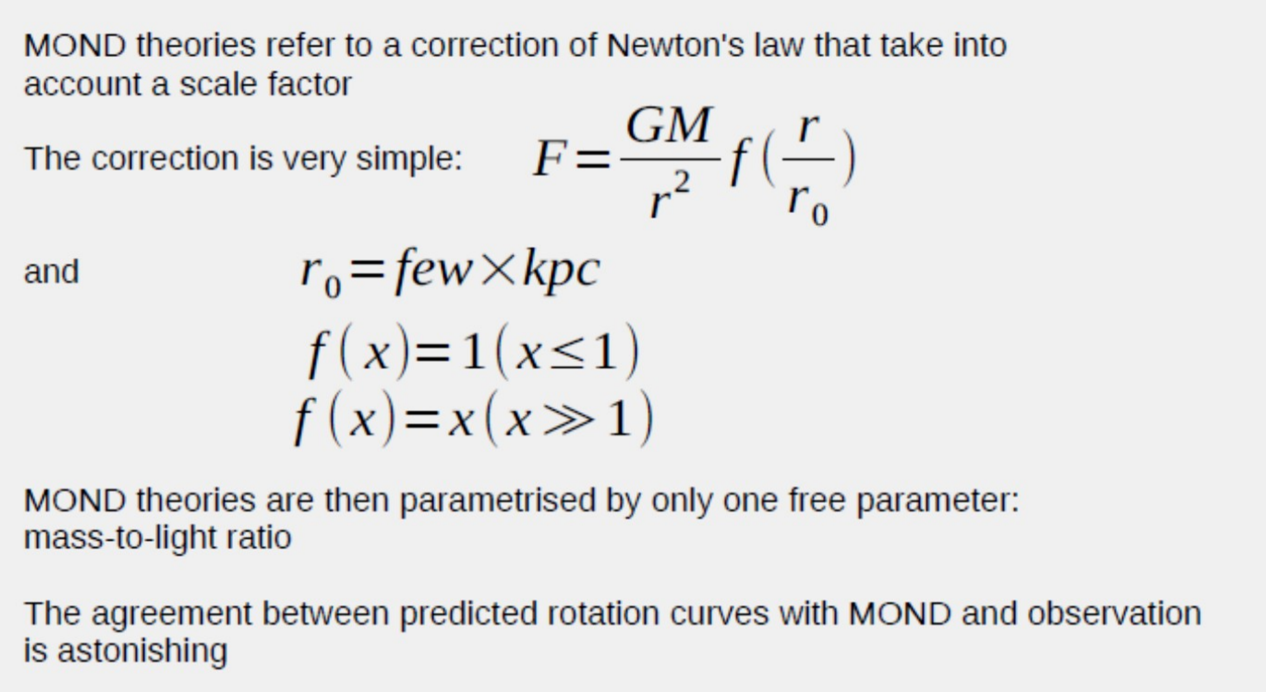


→ **stable on cosmological scales**



A large amount of not-luminous matter must populate galaxy bulks.

...or incomplete understanding of gravitation?



MOND theories refer to a correction of Newton's law that take into account a scale factor

The correction is very simple: $$F = \frac{GM}{r^2} f\left(\frac{r}{r_0}\right)$$

and $$r_0 = few \times kpc$$

$$f(x) = 1 \, (x \leq 1)$$
$$f(x) = x \, (x \gg 1)$$

MOND theories are then parametrised by only one free parameter: mass-to-light ratio

The agreement between predicted rotation curves with MOND and observation is astonishing

→ could explain 1 out of 3 evidences: it fails on the cluster scale and on observed lensing and anisotropy effects

Dark matter puzzle

DM exists (not 100% accepted conclusion)...

but DM origin and nature is still unknown:

I. Modified Newtonian Gravity (MOND) may not require DM

II. Something completely different and unexpected (not-particle DM candidates)

→ **M**assive **A**strophysical **C**ompact **H**alo **O**bjects (*MACHOs*): highly condensed object as neutron stars, brown and white dwarfs, **primordial black holes** [arXiv:1906.05950]

III. Exotic subatomic candidates: similarly to the SM, *dark sectors* with new particles content may exist

→ postulate particle-like nature

Dark matter particle candidates

DM candidate prerequisites:

- ✓ average velocity of a self-gravitating sphere <v>~ 235 km/s (assumed Boltzmann distribution)
- ✓ Cold, non-relativistic candidate and stable
- ✓ Only very weakly interactions (*dark*)
- ✓ Provide the right *relic density*

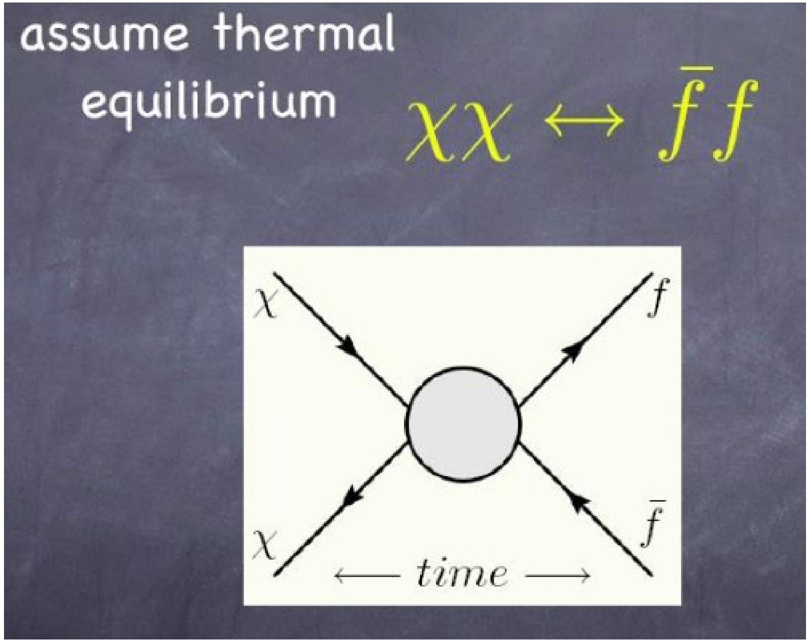
experimental input from cosmological observation.

- **Neutrinos:** relativistic (hot) candidates
- **Sterile Neutrinos:** cold DM that may explain the neutrino masses problem
- Weakly Interacting Massive Particles (**WIMPs**): match new particle candidates from supersymmetric models (*neutralino*)
- **QCD Axions:** Peccei-Quinn solution to QCD fine-tuning problem

Weakly Interacting Massive Particles (WIMP)

- Dominant model for more than three decades, assume thermal equilibrium in early universe between SM particles (f) and DM (χ)

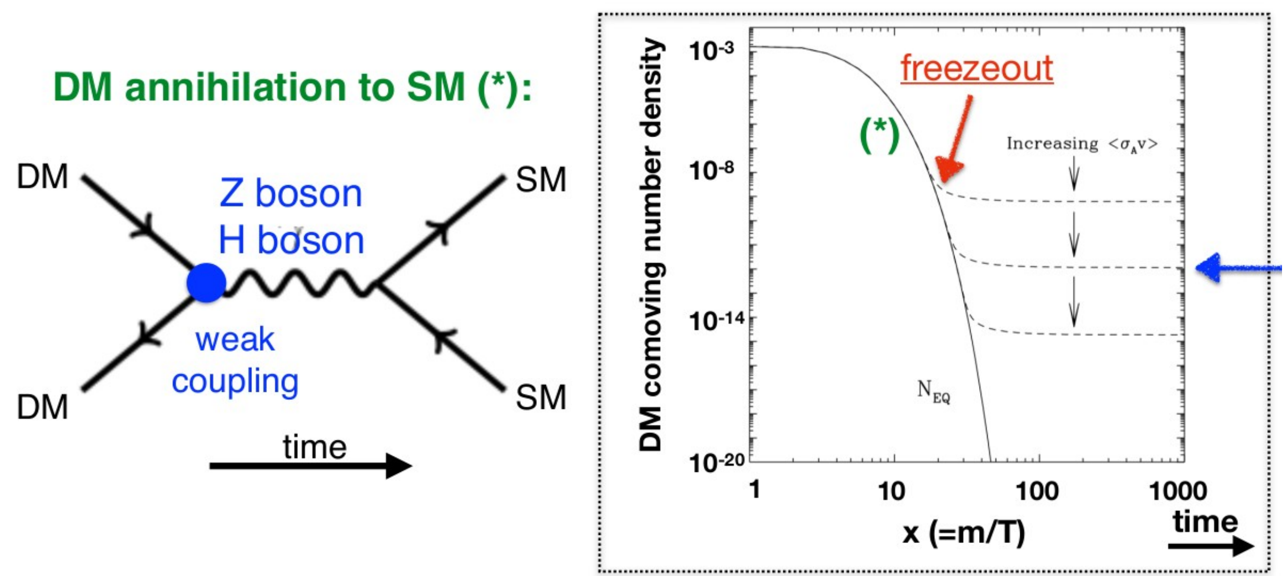
$$n_{\mathrm{DM}}^{(\mathrm{eq.})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$



Weakly Interacting Massive Particles (WIMP)

- As the universe expands, the DM number density is exponentially suppressed as $e^{-m/T} \rightarrow$ no more DM annihilations are possible
- DM abundance is frozen at the **relic density**: $\langle \sigma v \rangle = 10^{-26}$ $cm^3 s^{-1}$

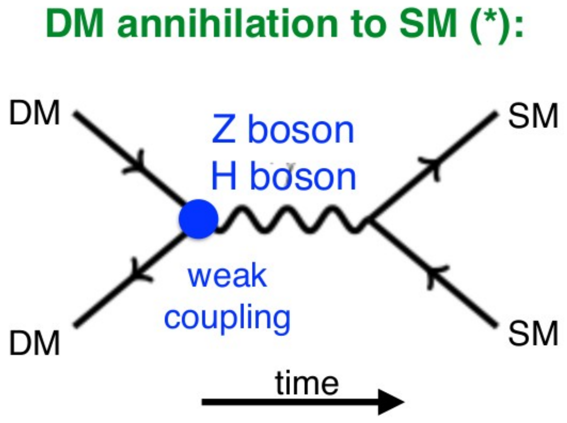
Thermal relic density: *freeze out* mechanism

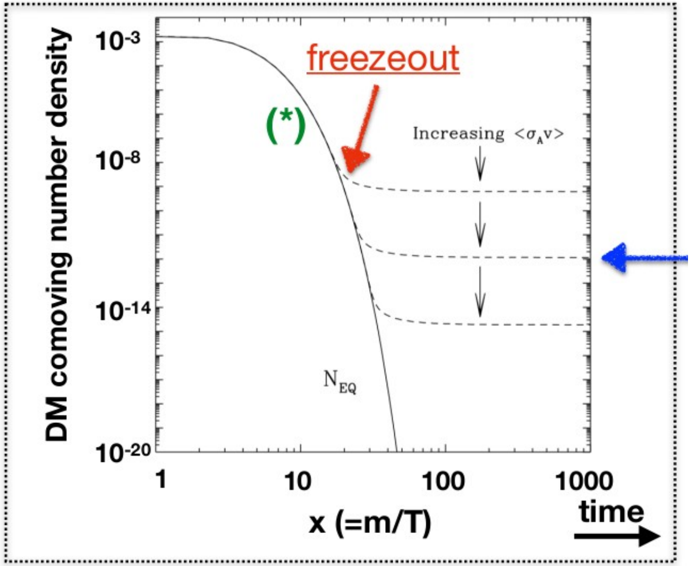


The WIMP “miracle”

- As the universe expands, the DM number density is exponentially suppressed as $e^{-m/T}$ → no more DM annihilations are possible
- DM abundance is frozen at the **relic density**: $<\sigma v> = 10^{-26}$ $cm^3 s^{-1}$
- Any weak-scale particle ~O(100GeV) freezes out at the correct cross section → **WIMP “miracle”**

Thermal relic density: *freeze out* mechanism



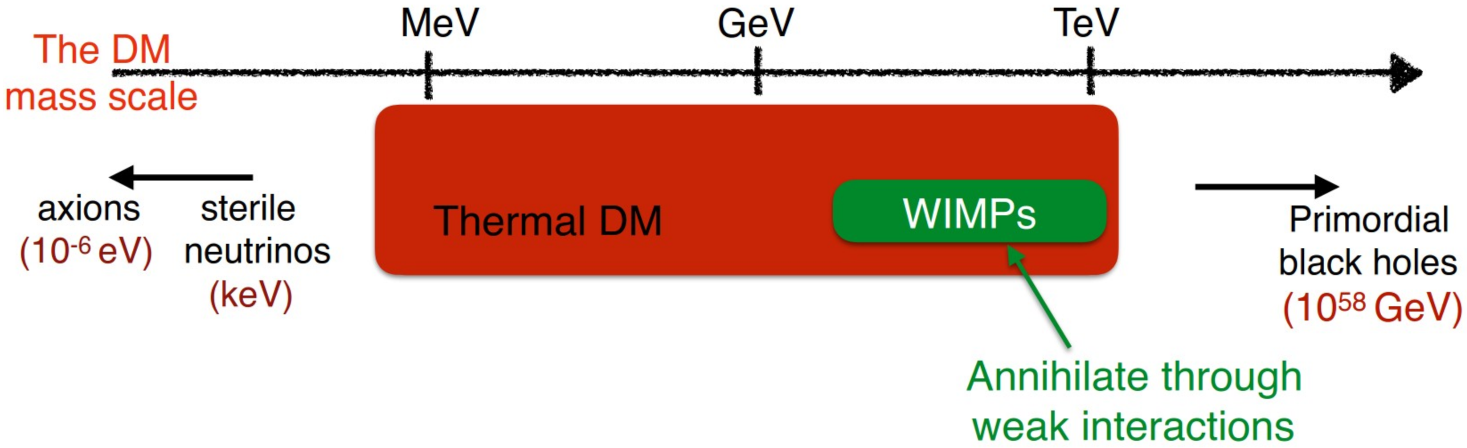


BUT…more recent constraints exclude vanilla WIMP models

Dark matter mass scale

- We do not know the DM mass scale

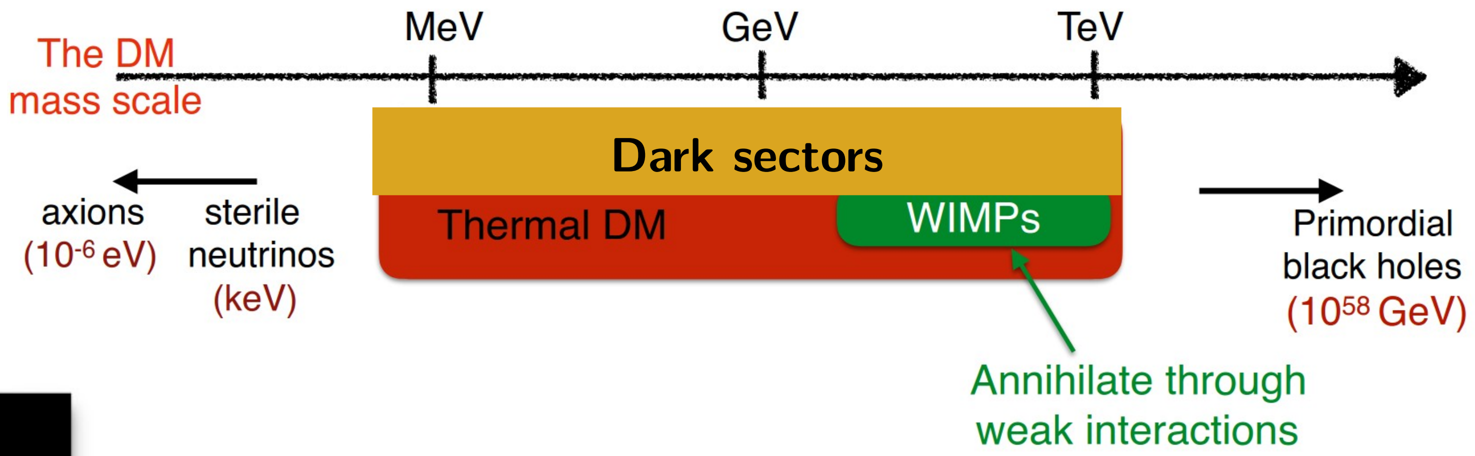
→ different searching strategies and techniques



Dark matter and dark sectors

- We do not know the DM mass scale

→ **different searching strategies and techniques**



The DM mass scale

MeV

GeV

TeV

Dark sectors

Thermal DM

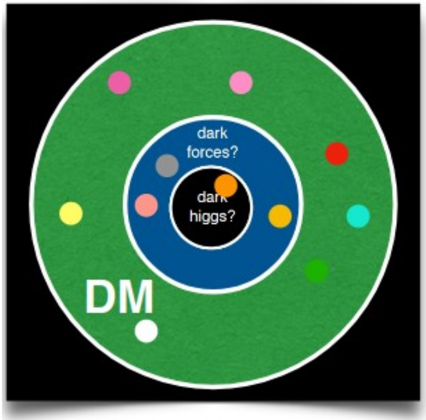
WIMPs

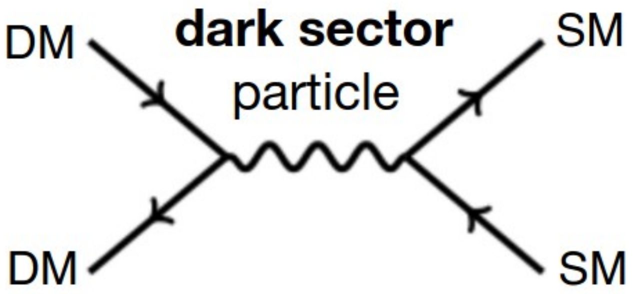
axions (10^{-6} eV)

sterile neutrinos (keV)

Primordial black holes (10^{58} GeV)

Annihilate through weak interactions



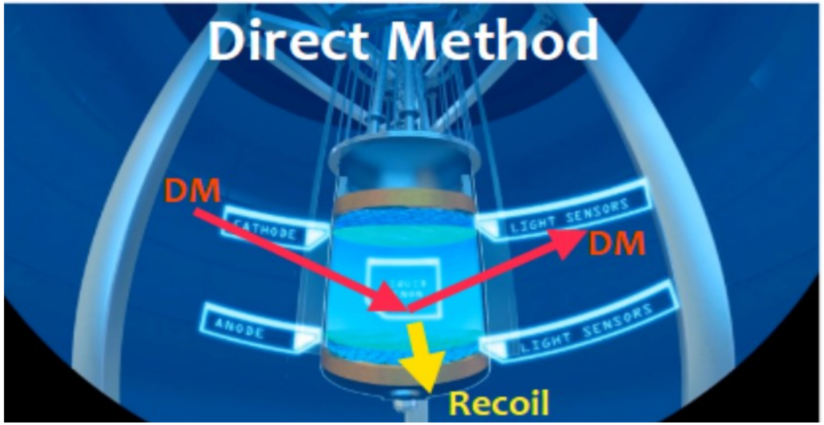


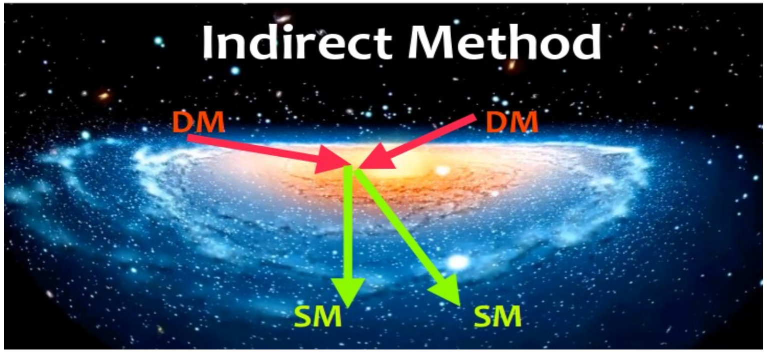
Hidden (**neutral** under SM interactions) sector that communicates with SM through a **portal** (new mediator)

Dark matter detection

How to search for it?

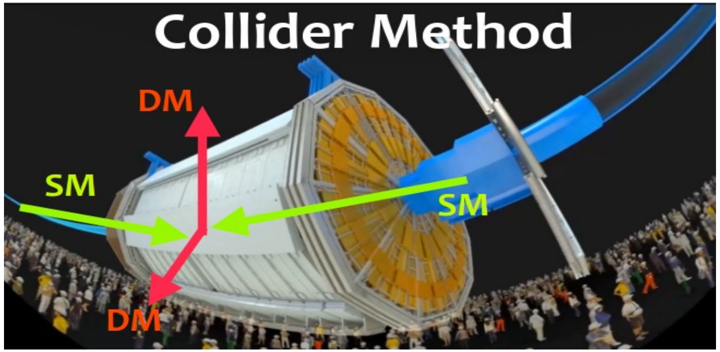
1) Detect the energy of *nuclear(electron) recoil*





2) Detect the *flux of visible particles* produced by *DM annihilation*, *decays* or *conversions*

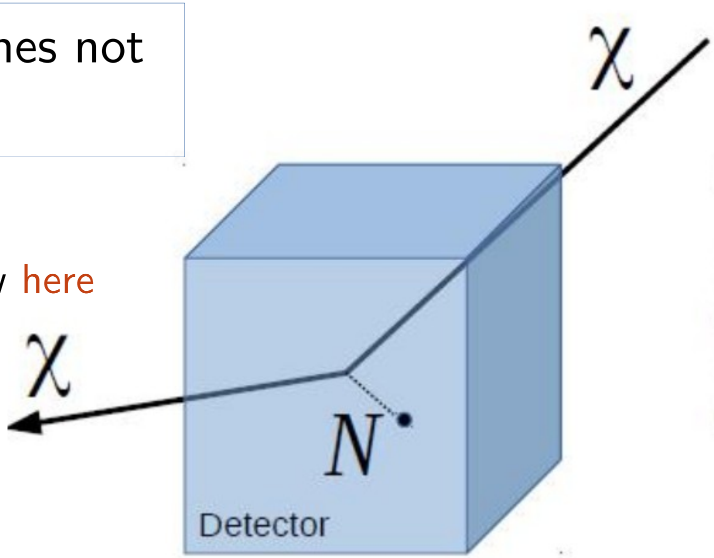
3) If DM weakly couples to SM it can be produced in *SM particles annihilation* at ***accelerators (colliders, fixed-target experiment)***

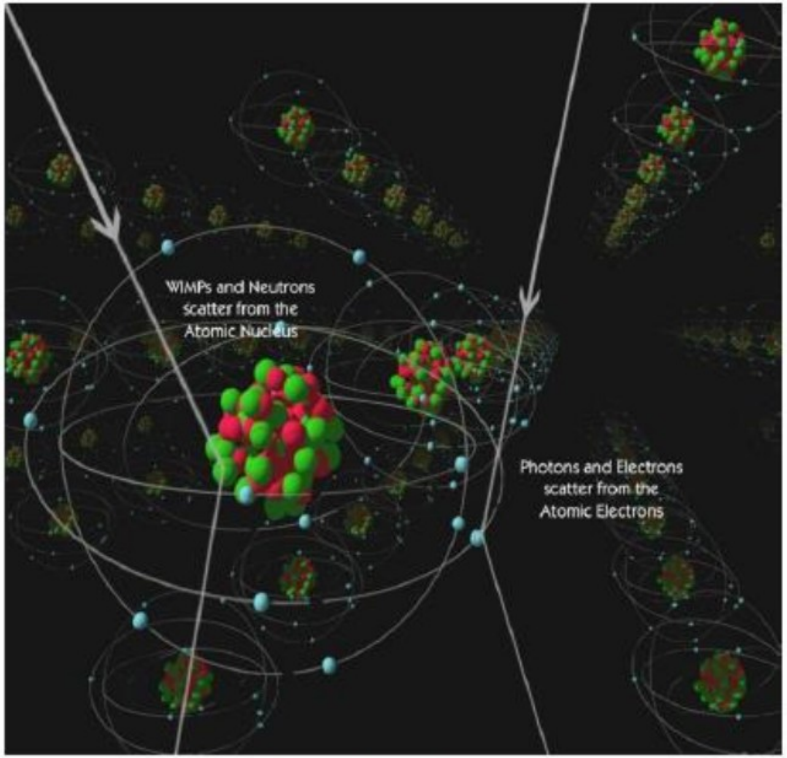


Principles of direct detection

Disclaimer: direct searches not treated in this seminar

- For more details interesting (though older, 2017) review here





Type of detectors:

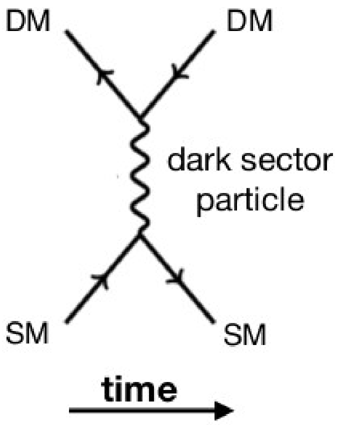
- Liquid gas (2-phase)
- Cryogenic detectors
- Scintillation
- Bubble chambers...

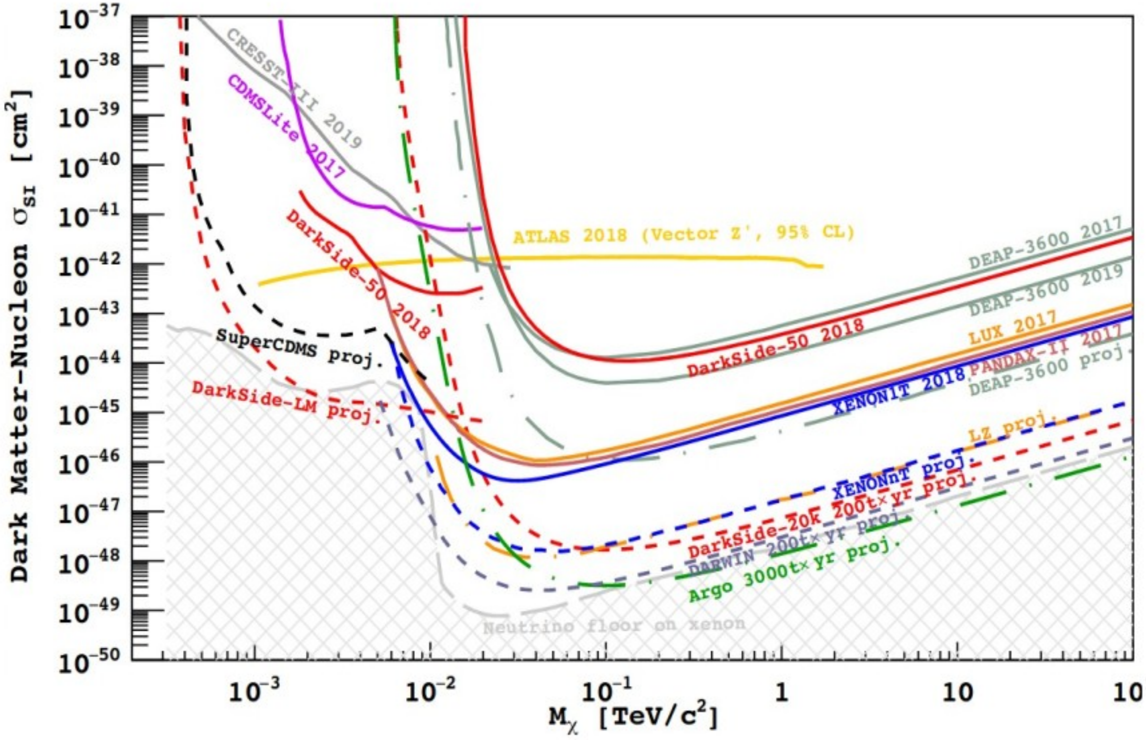
Type of interactions:

- Collisions with atomic nuclei
- Elastic scattering
- Low energy recoil

Direct detection (weak) bounds

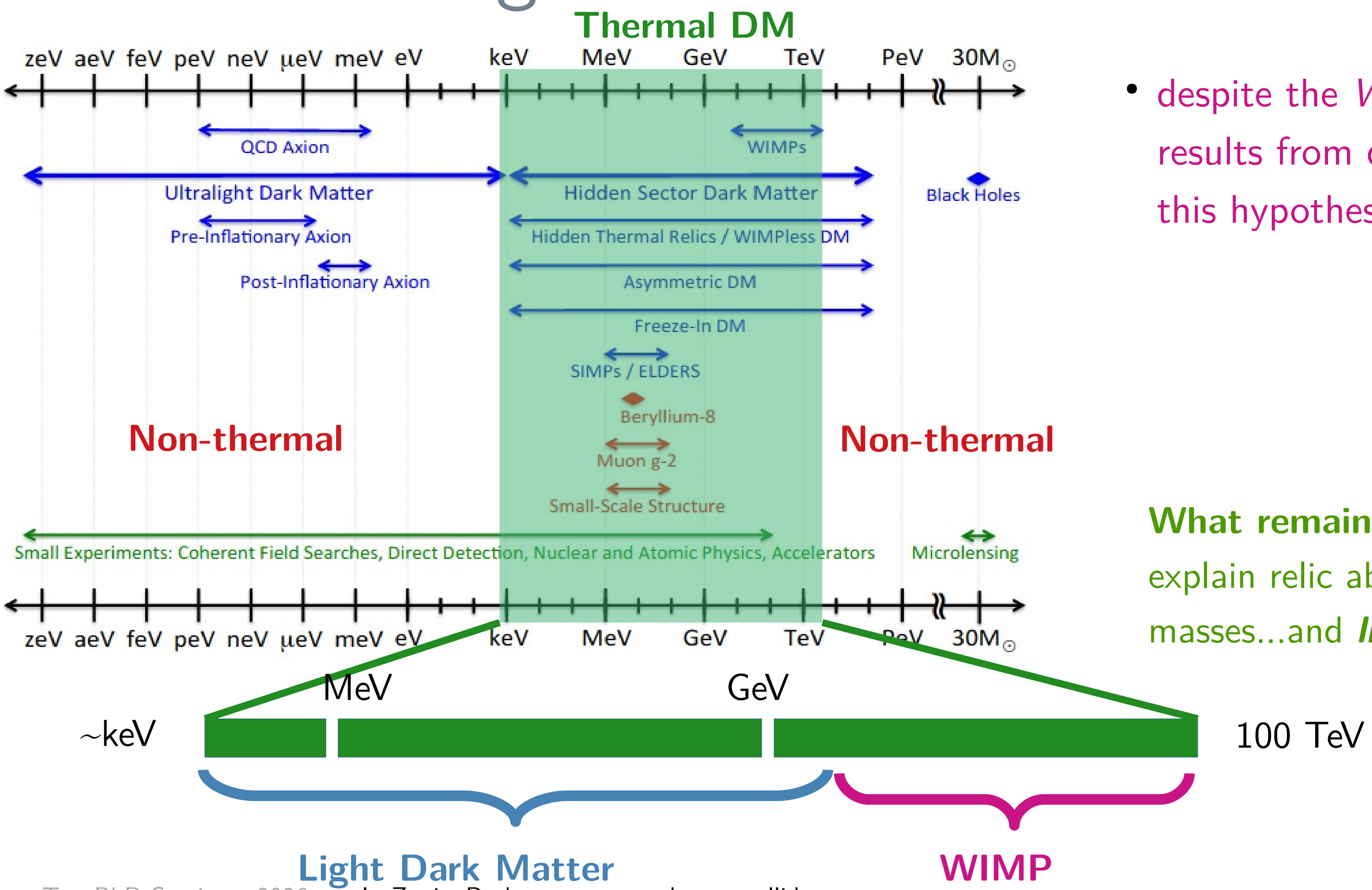
- Lower energy thresholds for the scattering recoil allow to access masses **above GeV scale**





- Sensitivities and upper limits on WIMP-nucleon spin-independent scattering cross section (European Strategy, Granada 2019, nice summary here)

Light dark matter scenario



- despite the *WIMP miracle*, null results from direct searches disfavor this hypothesis;

What remains? Sterile neutrinos, could explain relic abundance and neutrino masses...and ***light dark sectors***

Dark sectors beyond dark matter

- Not only to explain DM….**Dark sectors arise from different open issues** in SM
  - Theories addressing hierarchy problem (supersymmetric next-to-minimal BSM)
  - Theories explaining baryon-antibaryon asymmetry
  - Explanation of neutrino masses
  - Possible explanation of observed **anomalies in experimental data** (e.g.rare B meson decays, $(g\text{-}2)_\mu{}^{\dagger}$)

→ **signatures similar to dark matter searches**

Muon anomalous magnetic moment

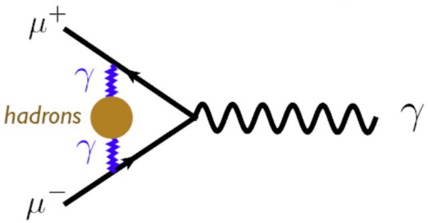
magnetic dipole moment
of charged particle

$$\vec{\mu} = \boxed{g_s}\left(\frac{q}{2m}\right)\vec{s}$$

spin

can be measured
very accurately

e.g.



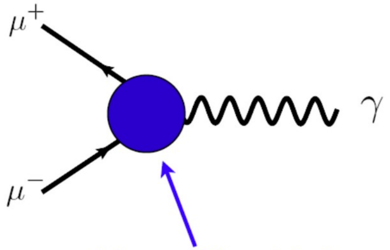
$g_s \neq 2$

(Standard Model)

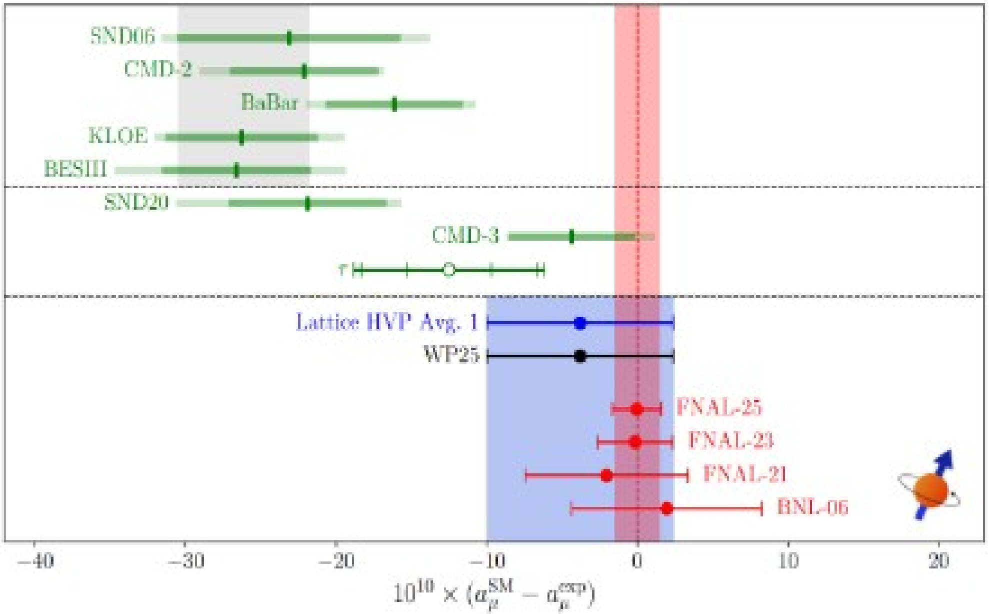
difficult to calculate precisely in Standard Model...

Standard Model
$(g_s-2)_\mu$ versus Data $\sim$ 3.6 σ deviation

Evidence for New Physics?

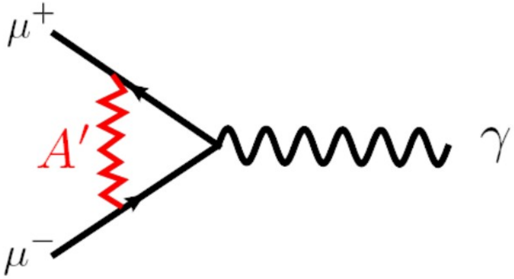


Loops of new particles could explain it... many possibilities



- New updates show no tension between $a_\mu{}^{SM} - a_\mu{}^{exp}$

A very “simple” possibility



consider not a *photon*…

but a “*massive*” or “*dark*” photon: A′

- mediates a new force
- weakly coupled to electrically charged matter
- focus on mass of A′ $\sim 1\ \mathrm{MeV} - 1\ \mathrm{GeV}$

→ A’ may explain the observed $(g_S\text{-}2)_\mu$: contribution depends only on ε and $m_{A'}$

A′ contribution is:

$$(g_s-2)^{A'}_{\mu} \simeq \frac{\alpha}{2\pi}\times\epsilon^2 \qquad (m_{A'}\ll m_\mu)$$

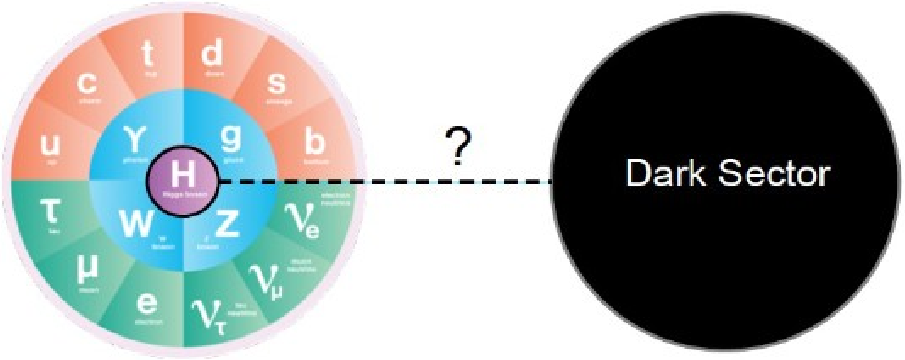
$$\simeq 10^{-3}\times\epsilon^2$$

SM/data discrepancy $\sim 10^{-9}$ → $\varepsilon \sim 10^{-3}$

Minimal dark sector models

Simplest formulation

- Postulate a new force under which SM particles are neutral. They feel its existence through the mixing between the new force mediator and SM gauge interactions

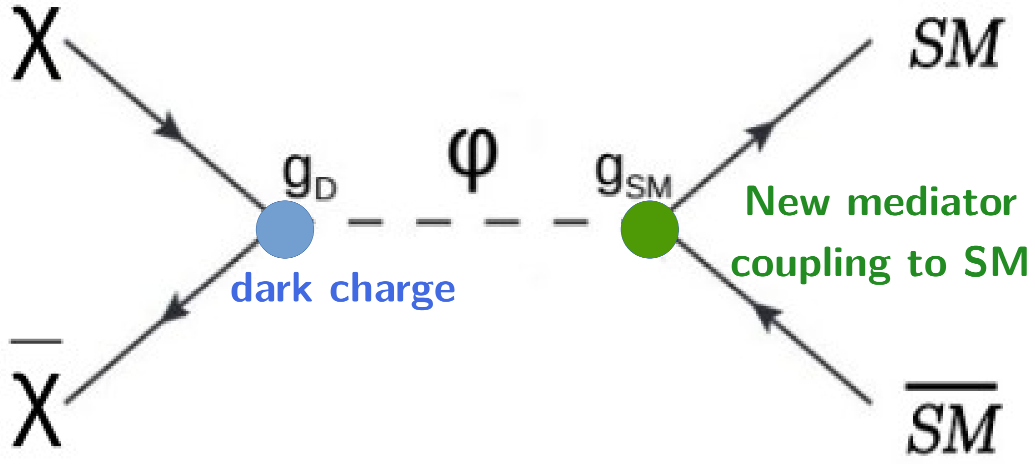


Light dark sector portals

- DM-SM thermalization requires new *portal* interactions → motivates the search for a light dark sectors mediator (φ)

$$\langle \sigma v \rangle_{relic} \sim \frac{g_D g_{SM} m_\chi^2}{m_\phi^4}$$

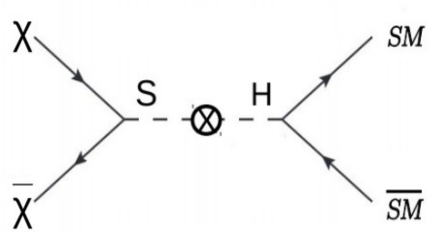
$$m_\phi^4 \leq \frac{m_\chi^2}{<\sigma v>} \text{ since g} < O(1)$$



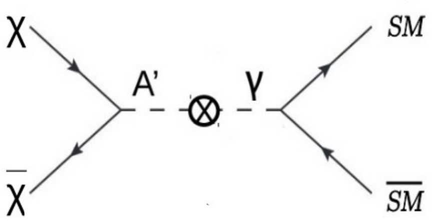
Light dark matter scenario requires the existence of new *light* mediators

Light dark sectors

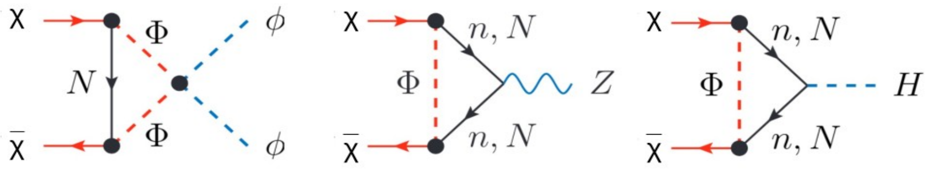
- Within allowed SM symmetries, 3 possible renormalizable portals with dimensionless couplings



1) Scalar

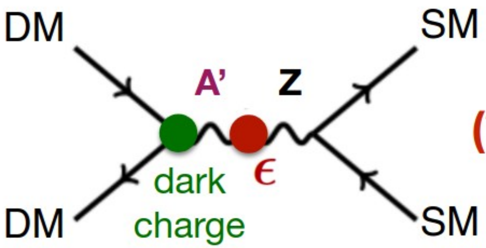


2) Vector(*)



3) Neutrino portal

Example:



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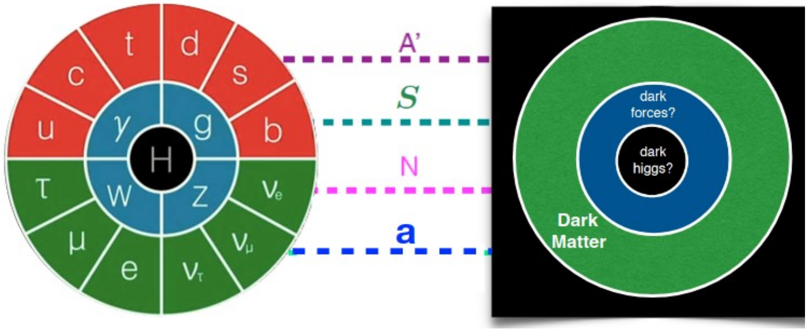
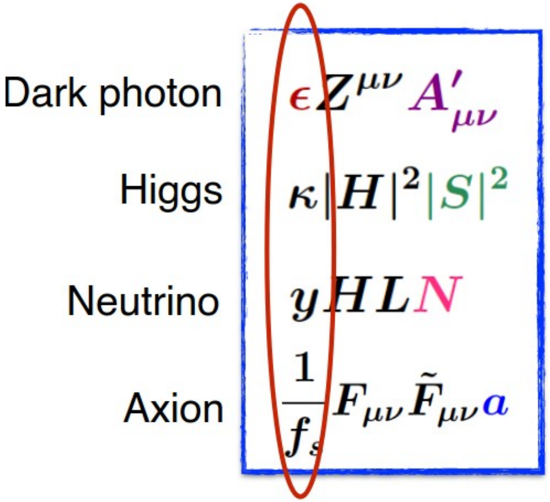


+ a not-renormalizable pseudo-scalar portal assuming Axion-Like Particles (ALPs) as mediators:

Experimental thermal target

- For thermal DM production via freeze-out **not too small coupling** is required

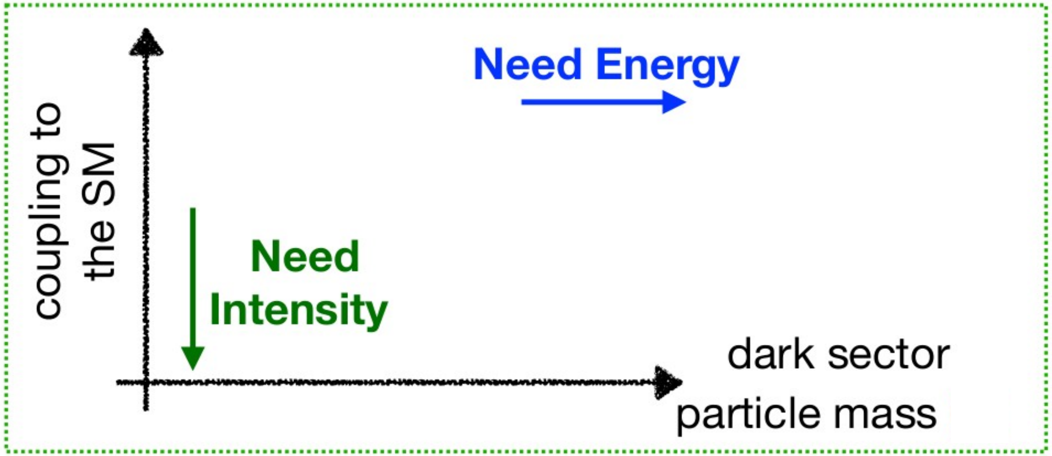


Dark photon $\epsilon Z^{\mu\nu} A'_{\mu\nu}$

Higgs $\kappa |H|^2 |S|^2$

Neutrino $y H L N$

Axion $\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$



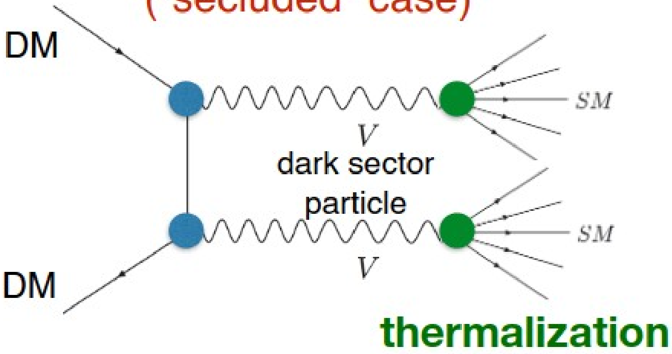
→ **SM weakly coupled to dark sector, possible searches at collider**

Possible thermal targets

Mainly two classes of thermal DM:

One (or more) particles of the dark sector **are lighter than DM**

("secluded" case)



→ **DM only virtually produced in SM annihilation**

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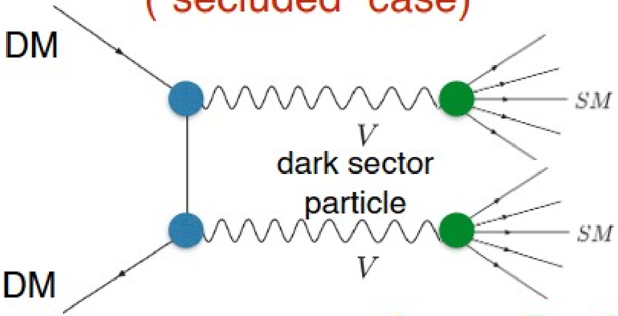
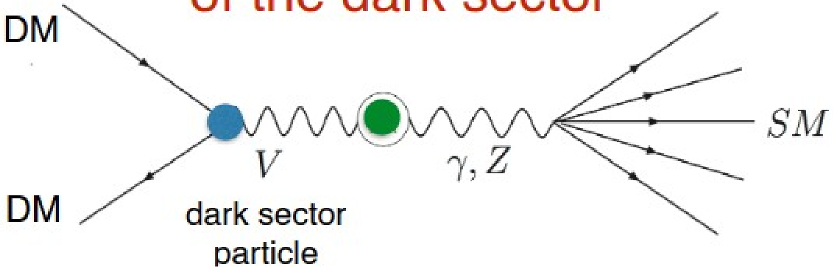


thermalization

→ **DM only virtually produced in SM annihilation**

DM is the lightest state

of the dark sector



→ **DM kinematically accessible**

- Relic abundance regulated by ●x● as a function of the DM candidate mass

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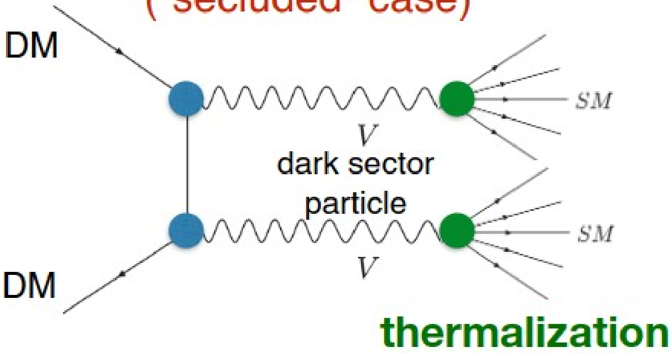

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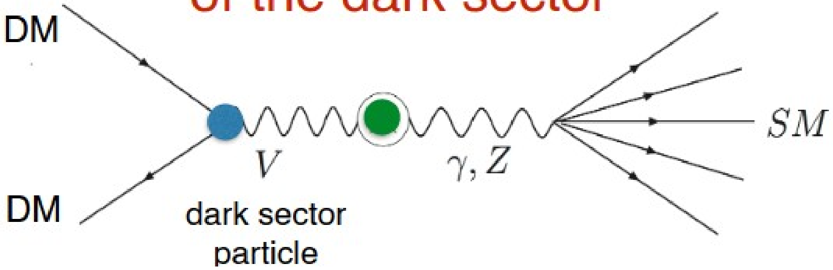


→ **DM kinematically accessible**

- Relic abundance regulated by 🔵x🟢 as a function of the DM candidate mass

Experimental signatures at accelerators:

VISIBLE decay of dark sector particle into SM particles,

V→ SM SM

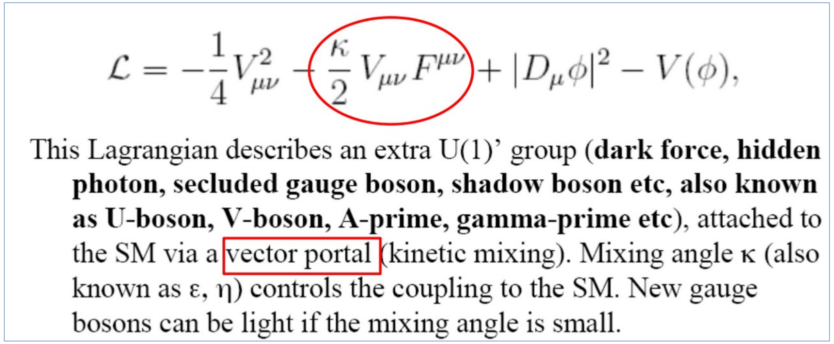
INVISIBLE decay of dark sector particles to DM,

V→ DM DM

Vector portal: dark photons

- Dark sectors are more generic than light DM and *a priori* unconstrained in their structure
- Usually they contain at least a new U(1) gauge group with an associated spin-1 massive boson A' → the ***dark photon***
- Interaction with the SM particles are mediated by the *kinetic mixing* with the SM photon with a strength ε:

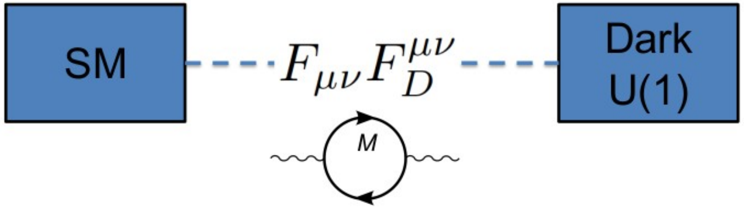
$$\mathscr{L}_{A',\gamma} = \frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$



$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu}^2 + \boxed{\frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu}} + |D_\mu \phi|^2 - V(\phi),$$

This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

[Holdom, paper]



Summary 1.0

- Astrophysical and cosmological observations (+ anomalies) might point out the **existence of a new GeV scale force** weakly coupled to the Standard Model through kinetic mixing
- In the **simplest formulation**, there is only one new particle, the **dark photon**, and **two parameters**: *mass* and *mixing* with the SM
- In the **next-to-simplest formulation**, we gain one additional particle, a **dark Higgs**, which provides mass to the dark photon through the "usual" Spontaneous Symmetry Breaking mechanism
  - Here the simplest assumption is that **dark matter is heavier** than the dark photon (secluded DS), decays of dark photons to dark matter are kinematically prohibited, $\mathbf{m_{A'} < 2m_x}$ → dark photon is compelled to decay to SM light particles as *electrons, muons, pions* and few others, depending on its mass (**visible decays**)

Summary 1.1

- Take home messages:

  → **1. search for DM and dark sectors well motivated**

  → **2. relatively simple models producing observable signatures**

  → **3. heavy DM hypothesis defined the experimental activity of the past decades in searching for visible dark photons**

- Phenomenological consequence of simplest DS: may look for dark photons replacing SM photons paying factor ε^2
- If give up with heavy DM and assume DM lighter than dark photon exists,
  - V→ SM SM highly suppressed (ε^2)
  - V→ DM DM is allowed, possible to look for **invisible decays** of dark photon

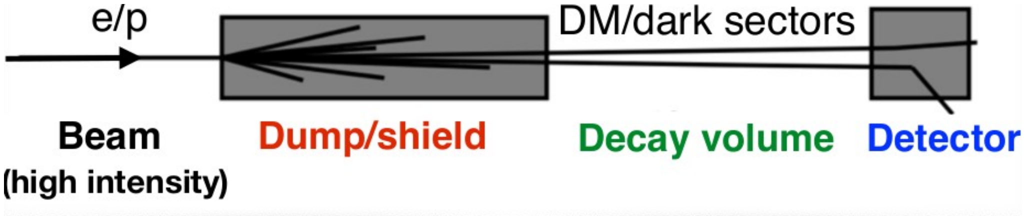
Search methods
and experimental facilities

Light dark sectors at accelerators

- Three main ways to experimentally search for dark forces at accelerators:
  - e^-e^+ collisions
  - rare meson decays (wherever produced)
  - Fixed target experiments (e^-, e^+, proton beams)

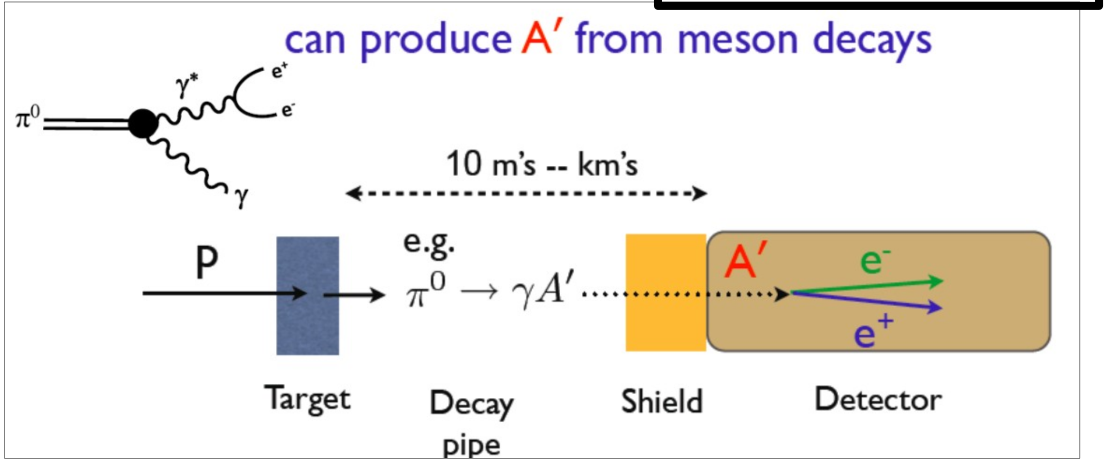
→ Only some fixed target experiments were designed explicitly for the dark photon search...

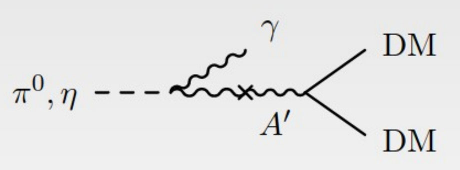
Dark photons at fixed-target experiment



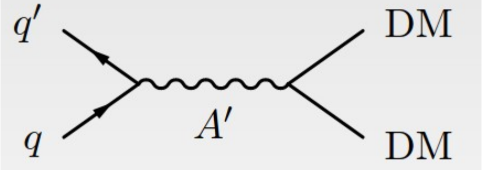
VISIBLE decays

- **Proton** beam dump (at neutrino facilities)
  - Look for neutral pion conversions to photons that may kinetically mix with the dark photon
  - Signal signature: **dilepton resonances,** long-lived particle, missing energy



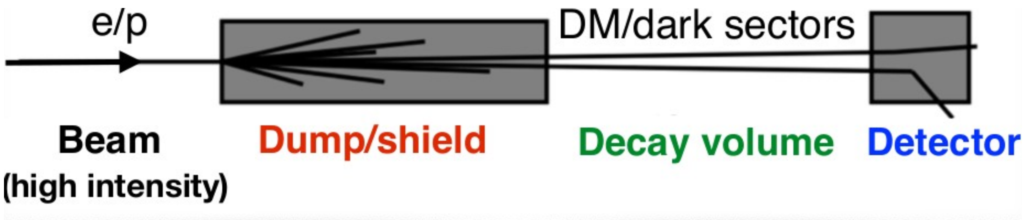


Via meson production



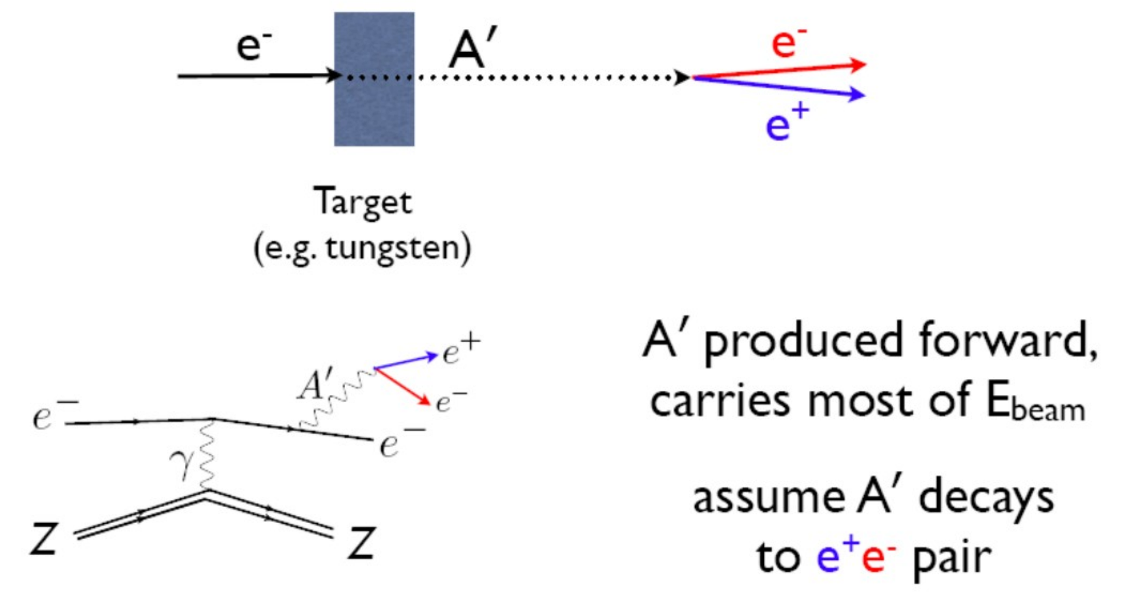
Direct production

Dark photons at fixed-target experiment



VISIBLE **decays**

- **Electron** beam-dump
  - Larger luminosity + compact special-purpose detectors
    - scattering cross section enhanced by nuclear charge coherence
  - Suitable to investigate ***vector* portals** for mediator masses $2m_e < m_{A'} < \text{GeV}$

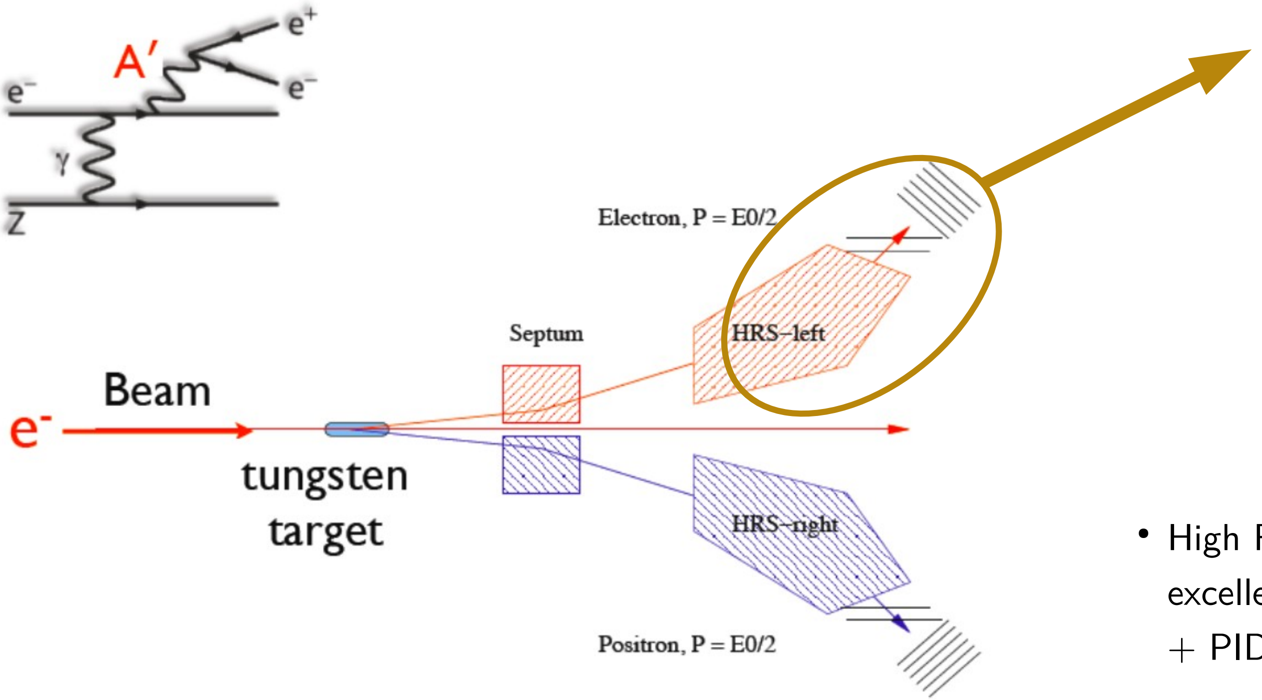


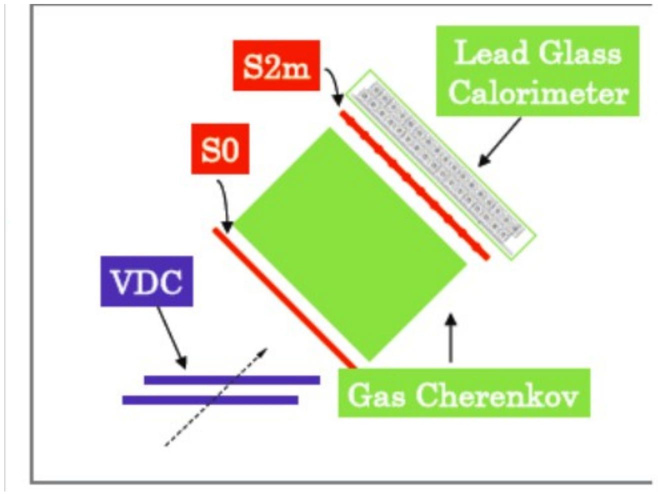
A′ produced forward, carries most of E_{beam}

assume A′ decays to e^+e^- pair

Experimental setup

APEX @ JLAB





- High Resolution Spectrometers (HRS) with excellent **angular and momentum resolutions** + PID capability

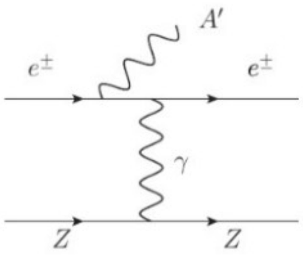
→ search for a peak in the reconstructed spectrum of e^+e^- invariant mass ($m_{A'}$)

- Relativistic kinematics reminder for $M \rightarrow m_1 + m_2$

$$= \sqrt{m_1^2c^4 + m_2^2c^4 + 2(E_1E_2 - \boxed{|\overrightarrow{p_1}||\overrightarrow{p_2}|}c^2cos\boxed{\theta_{12})}}$$

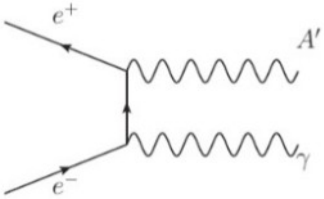
Positron enriched environment

a) A'-strahlung production



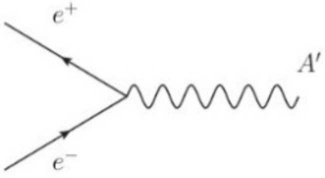
$\sigma \sim \varepsilon^2\alpha^3$

b)



$\sigma \sim \varepsilon^2\alpha^2$

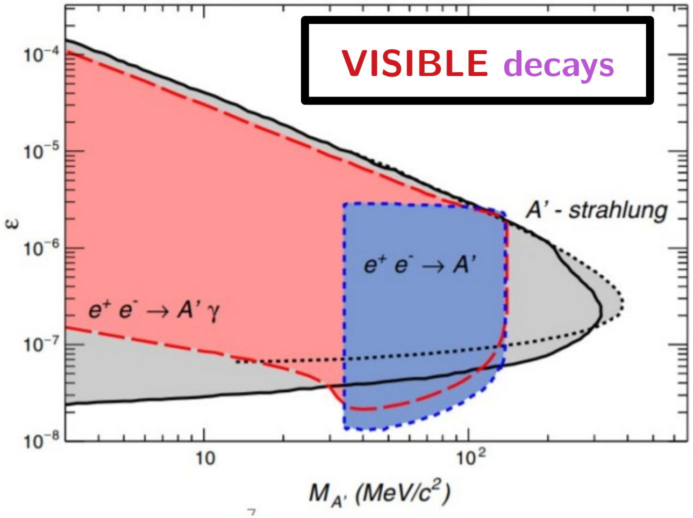
c)



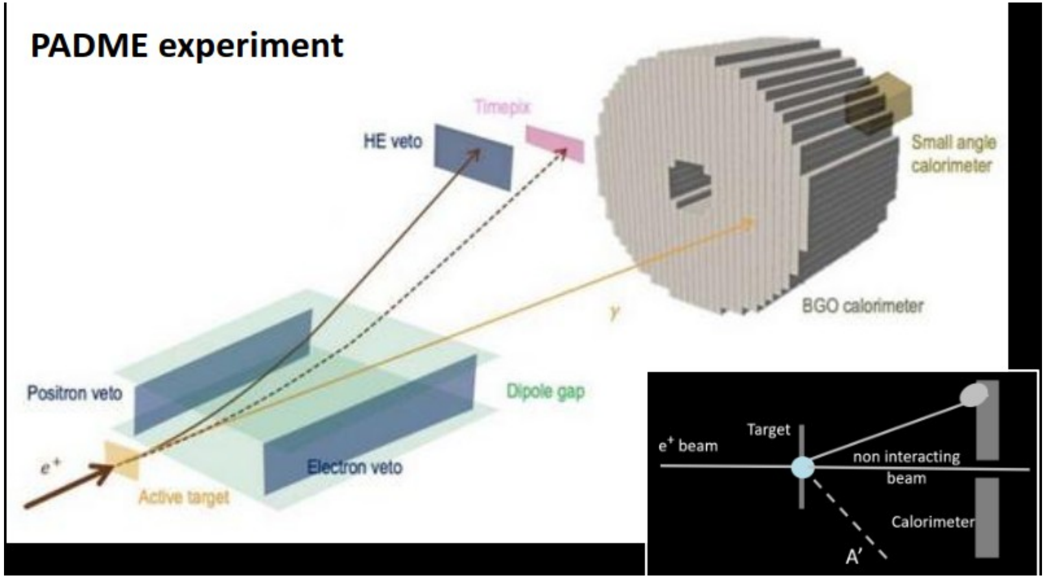
$\sigma \sim \varepsilon^2\alpha$

- Secondary positrons in EM showering contribute to the total A' yield with the non-resonant (b) and resonant (c) annihilation processes
  - → **resonant annihilation** is enhanced! May exploit *positron beams* (**PADME** experiment at Frascati, docu)

L.Marsicano *et al.* Phys. Rev. D 98, 015031 (2018)



PADME and the X17 saga

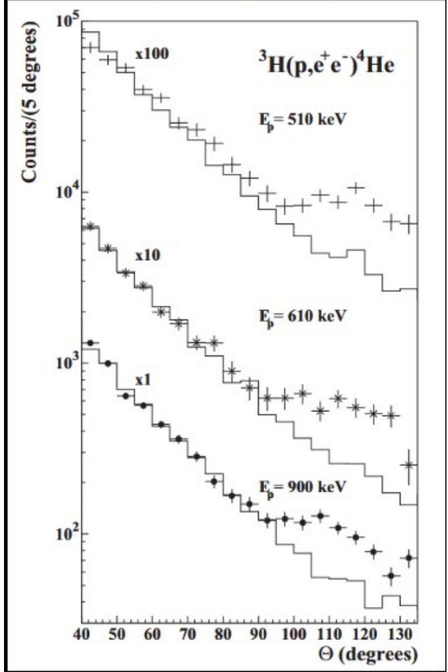


- 550 MeV positron beam from LNF Linac
  - Model-independent search in recoil mass spectrum ($e^+e^- \to \gamma A'$), can measure $e^+e^- \to \gamma\gamma$, $e^+e^- \to e^+e^-$

Prologue: Anomalous excesses in ^{8}Be, ^{4}He, and ^{12}C atomic measurements of internal pair creation.

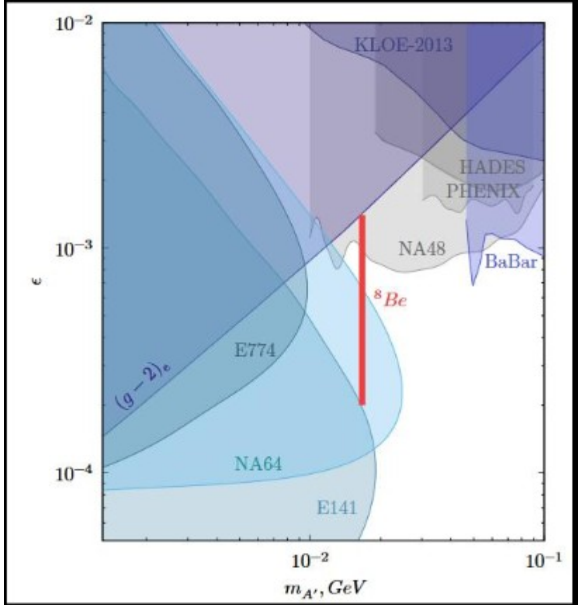
Possible explanation: new protophobic boson with 16.7 MeV mass (X17), ATOMKI experiment. Not entirely excluded by NA64 and MEG searches

Krasznahorkay *et al.*



PRC 104, 044003 (2021)

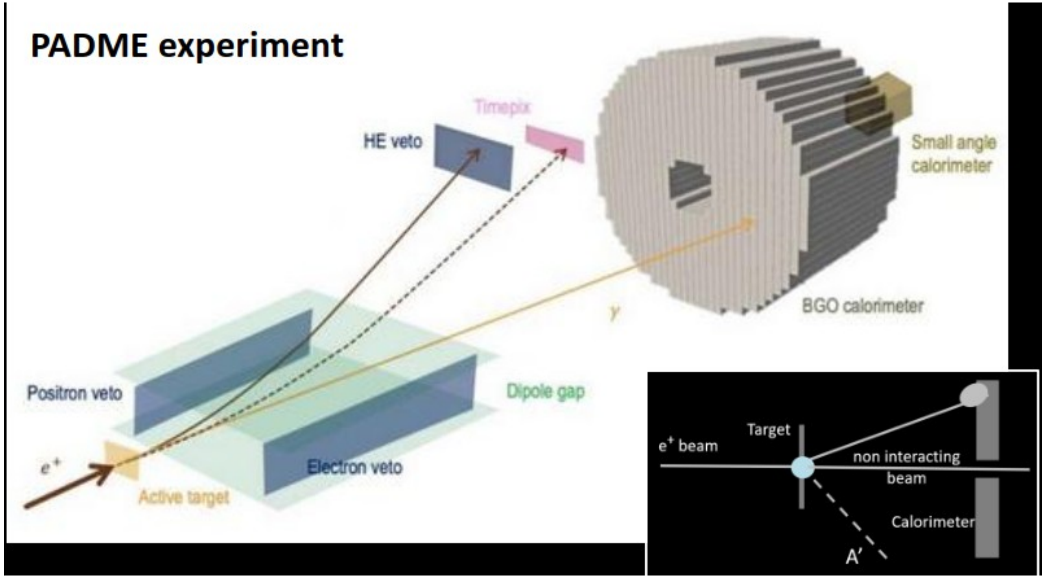
NA64 exclusion

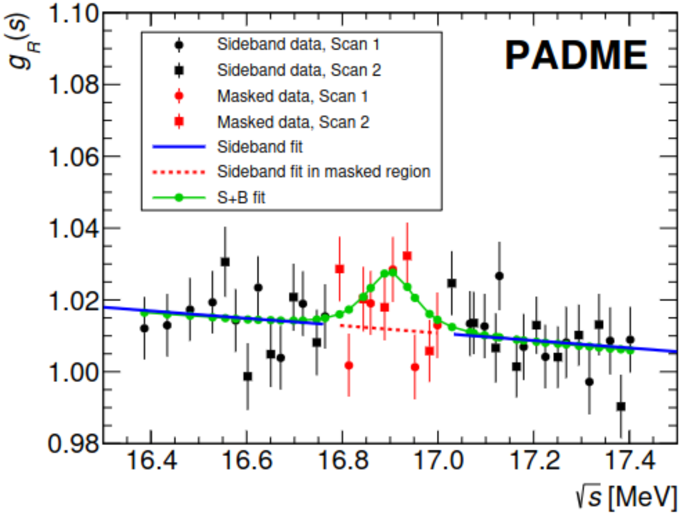


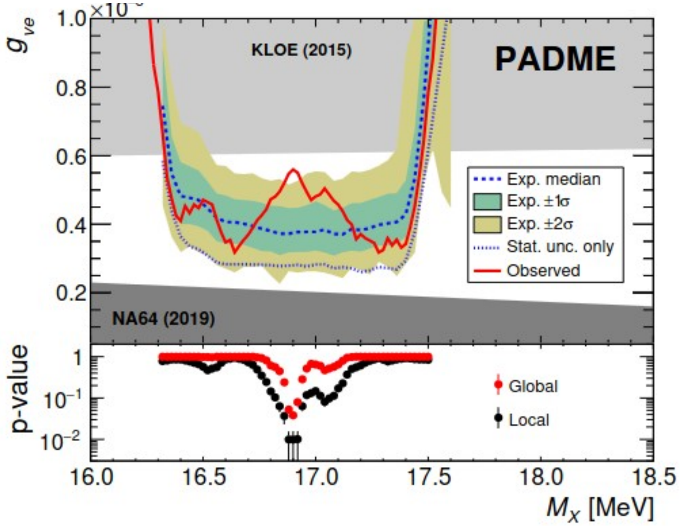
PRD 101 (2020) 7, 071101
PRD 104 (2021) 11, L111102

PADME and the X17 saga (II)

JHEP11(2025)007







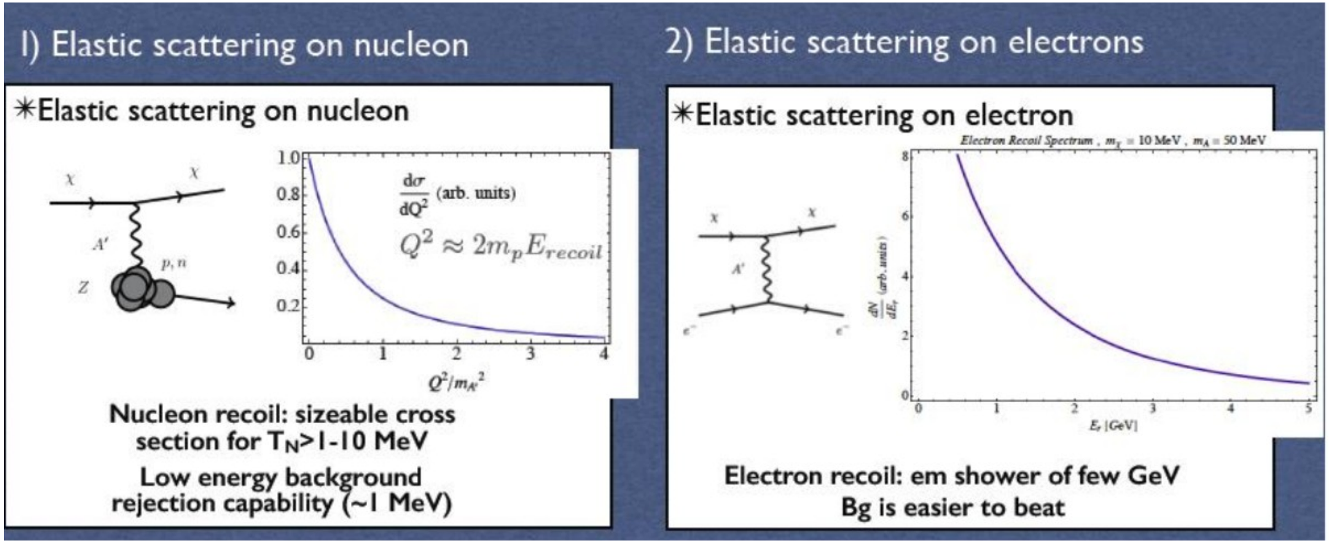
- Special run to search for X(17) in $e^+e^- \rightarrow e^+e^-$ events with resonance search, beam energy varied between 262-296 MeV
- Observe a 2.5σ bump consistent with X(17) production
- New run in preparation to take more data with improved detector to confirm signal significance

Normalized cross section (observed/SM):

$$g_R(s) = \left[1 + \frac{S(s; M_X, g_{ve})\varepsilon_{\rm sig}(s)}{B(s)}\right]$$

Light DM at fixed target

- Possible to **detect light DM $\boldsymbol{\chi}$** at e$^-$ beam dump experiment:
  - dark photons produced radiatively through A'-strahlung and secondary positron annihilation, A' → $\boldsymbol{\chi\chi}$
  - Detect elastic scattering on electron/nucleon



1) Elastic scattering on nucleon

✶Elastic scattering on nucleon

Nucleon recoil: sizeable cross section for T_N>1-10 MeV

Low energy background rejection capability (~1 MeV)

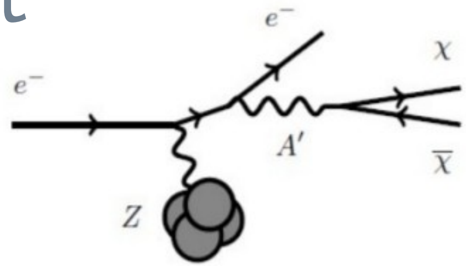
2) Elastic scattering on electrons

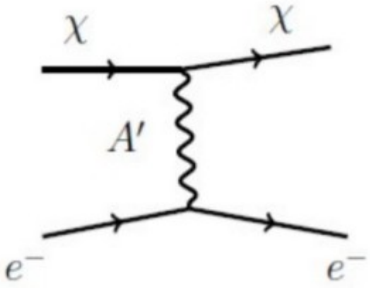
✶Elastic scattering on electron

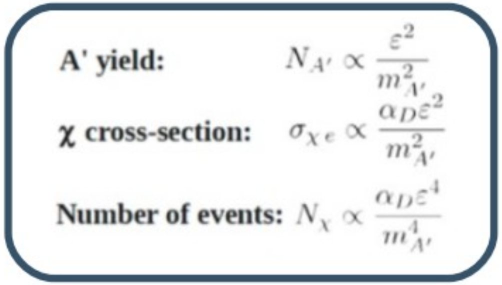
Electron Recoil Spectrum , m_χ = 10 MeV , m_A = 50 MeV

Electron recoil: em shower of few GeV

Bg is easier to beat







A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

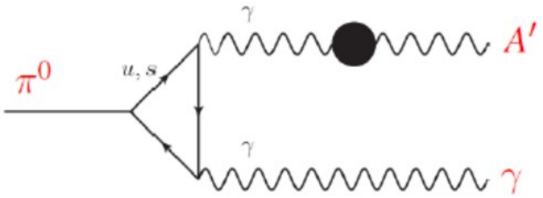
χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

→ Beam Dump eXperiment @Jefferson Lab, docu

DISCLAIMER

- Not treated here: limits on dark photon production in $\pi^0 \to \gamma A'$ processes from kaon beams

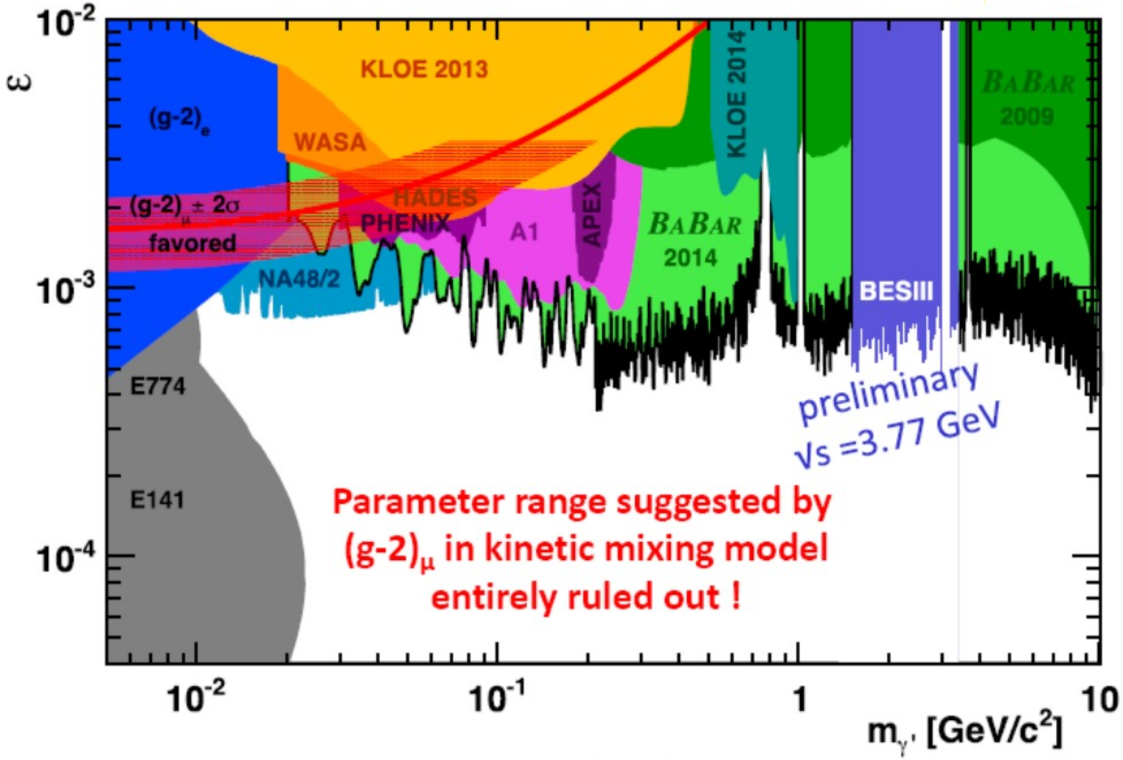


References: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.80.095024 and on **NA48/2 experiment @CERN**: here

- Complete the exploration of the ε - $m_{A'}$ phase space to eventually rule out the g-2 region (see next slide)

- **REMINDER:**
  - No signal ≠ no results!
  - No signal → set an **upper limit** on the maximum possible cross section consistent with lack of any observation (*statistical interpretation* of results)

Dark photons constraints

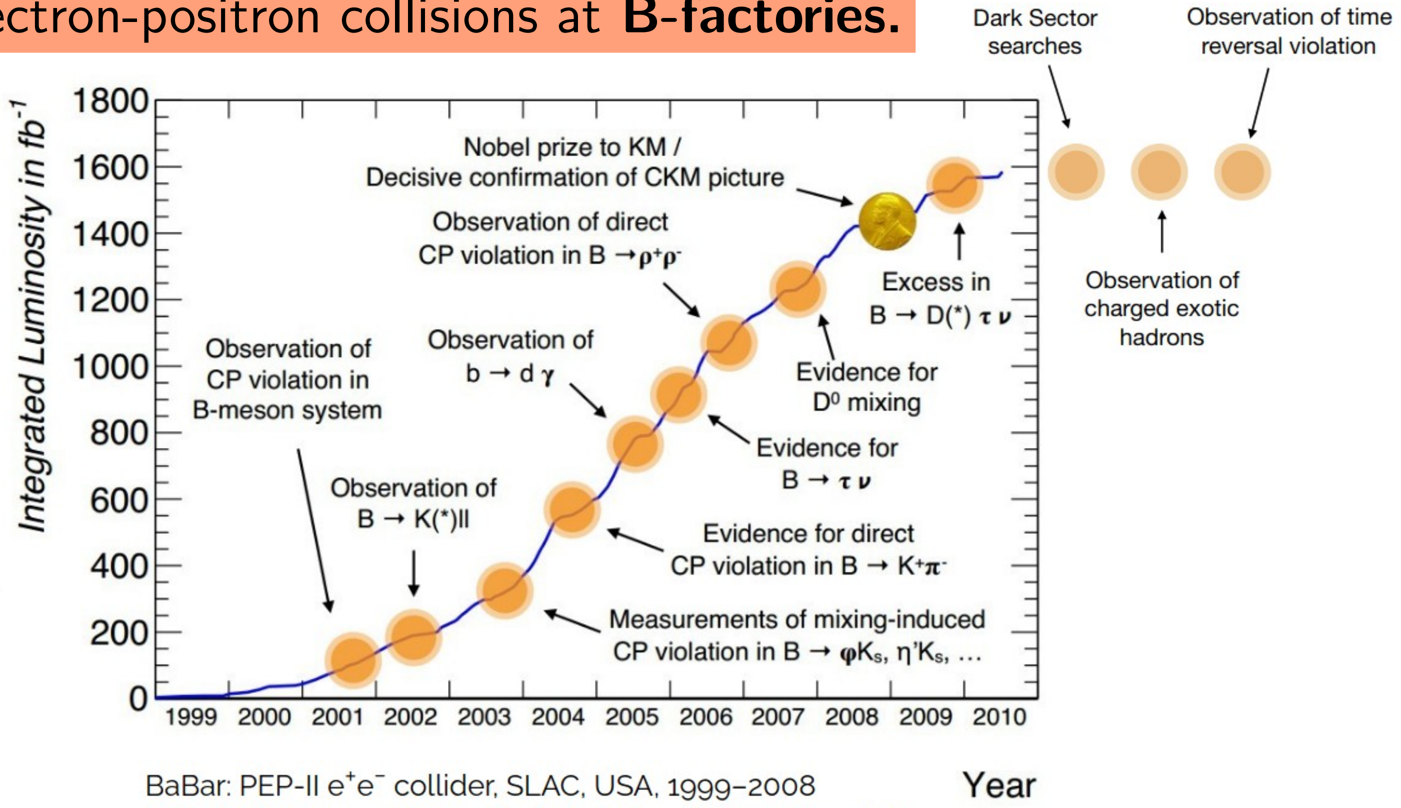


Remember: this is valid only for BR(A'→SM particles)=100%

Dark photon (visible) as an explanation of $(g-2)_\mu$ ruled out!

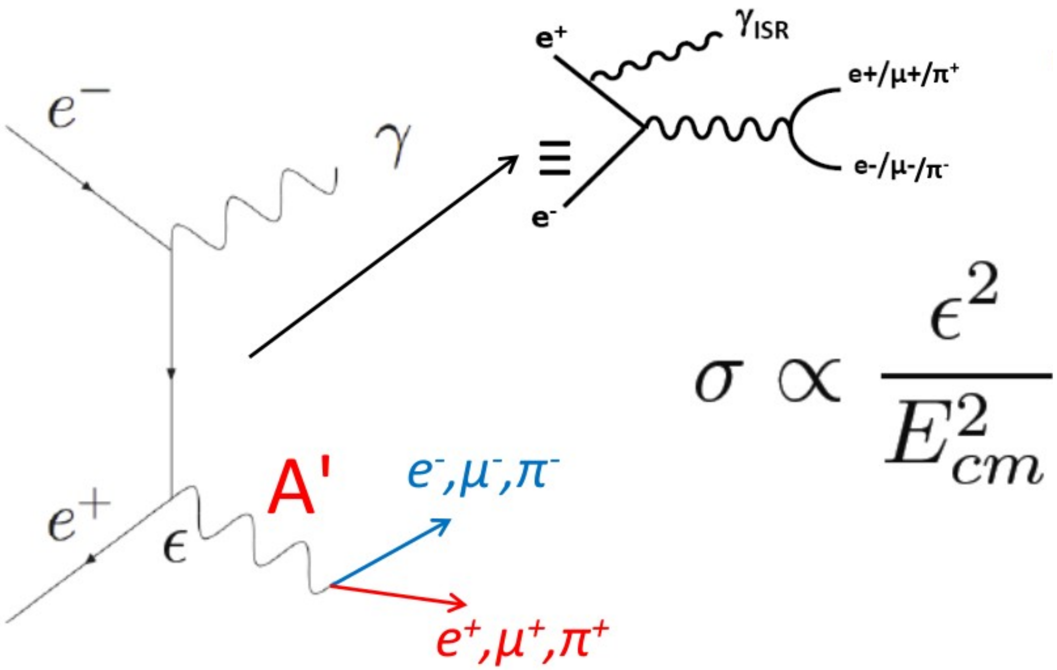
DISCLAIMER (II)

→ The rest of the seminar will focus on direct production in electron-positron collisions at **B-factories.**



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e– collider, KEK, Tsukuba, Japan, 1999–2010

Dark photon production in e^+e^- collisions



$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

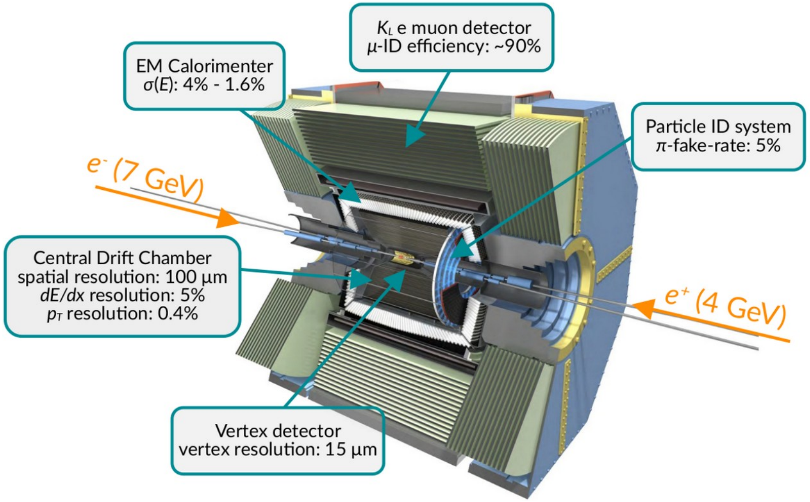
At low-energy, high intensity colliders (BaBar, Belle, KLOE..) production might be enhanced

Belle II experiment at SuperKEKB

- **Clean environment** at asymmetric energy e^+e^- collider + ~ **hermetic detector:**

  → at $\sqrt{s} = 10.58$ GeV: $\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb, B & τ, charm factory

  → known initial state + efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

beam current

beam-beam parameter

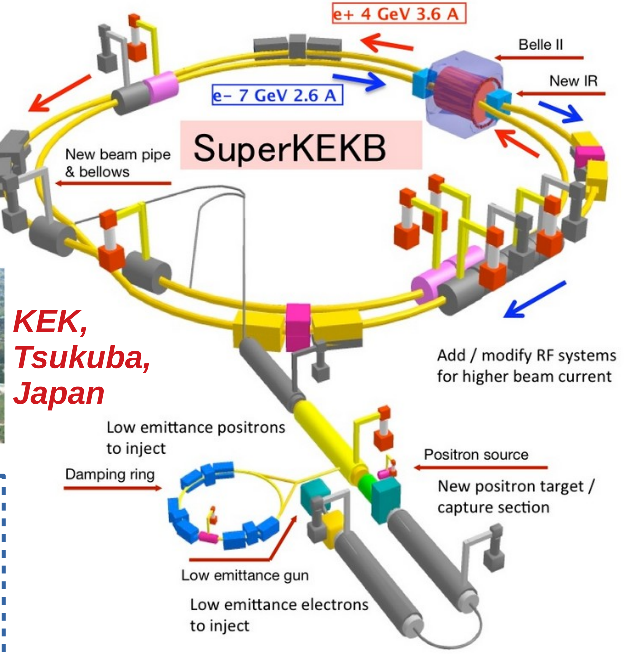
geometrical reduction factors

beam aspect ratio at the IP

vertical beta-function at the IP

World record luminosity of 5.1 x 10^{34} cm^{-1} s^{-2}

KEK, Tsukuba, Japan



- **GOAL:** 30 x KEKB peak luminosity, **L= 6 · 10^{35} $cm^{-2}s^{-1}$** *(nano-beam scheme technique*)*
- Collect 50 x Belle → 50 ab^{-1}

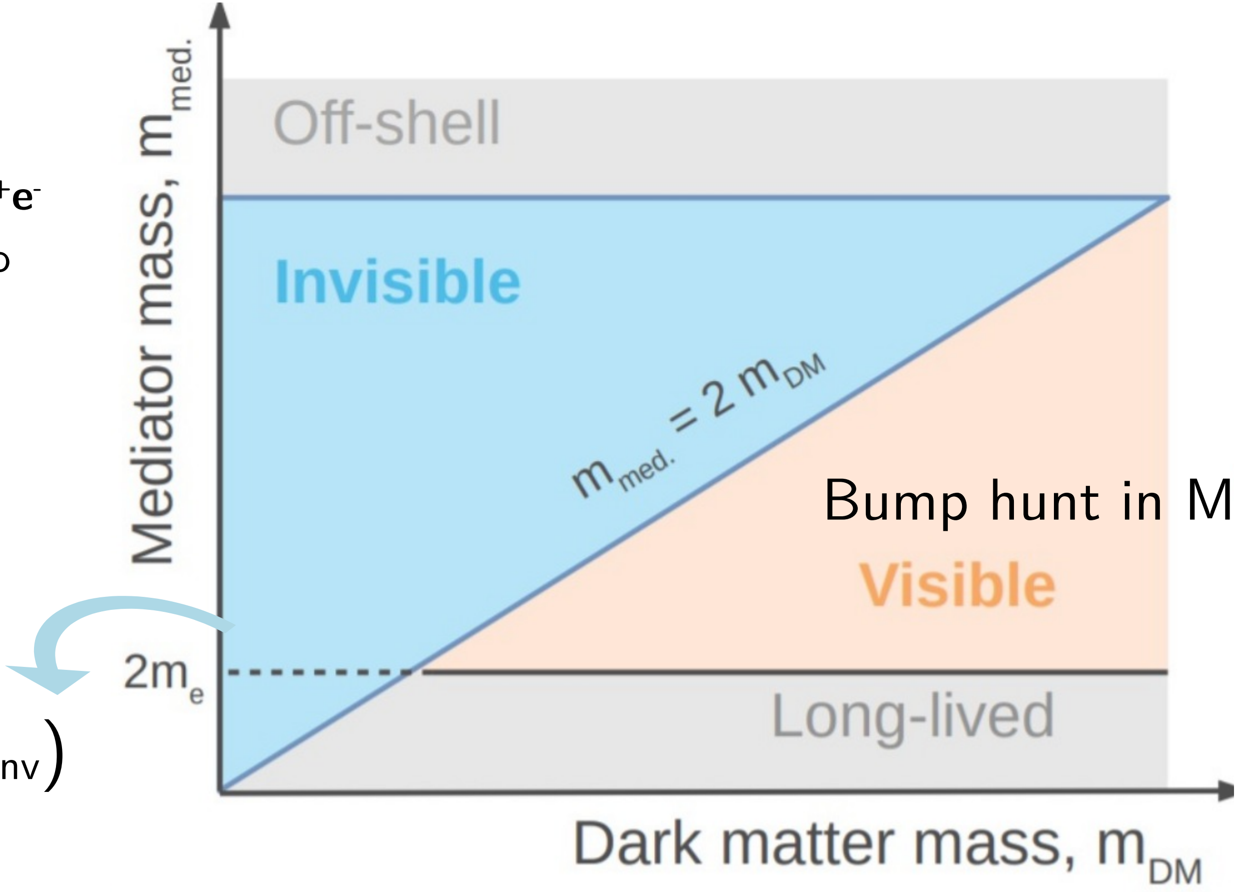
Accumulated > 0.7 ab^{-1} and unique energy scan samples during run 1 (2019-2022) and run 2 (2024 - present)

*https://arxiv.org/abs/0709.0451

Dark sectors searches at Belle II

Main experimental requirements

- Many models proposed, possibly very small couplings
- Profit from **known initial state in e^+e^- collision** + quasi-hermetic detector to investigate all possible signatures



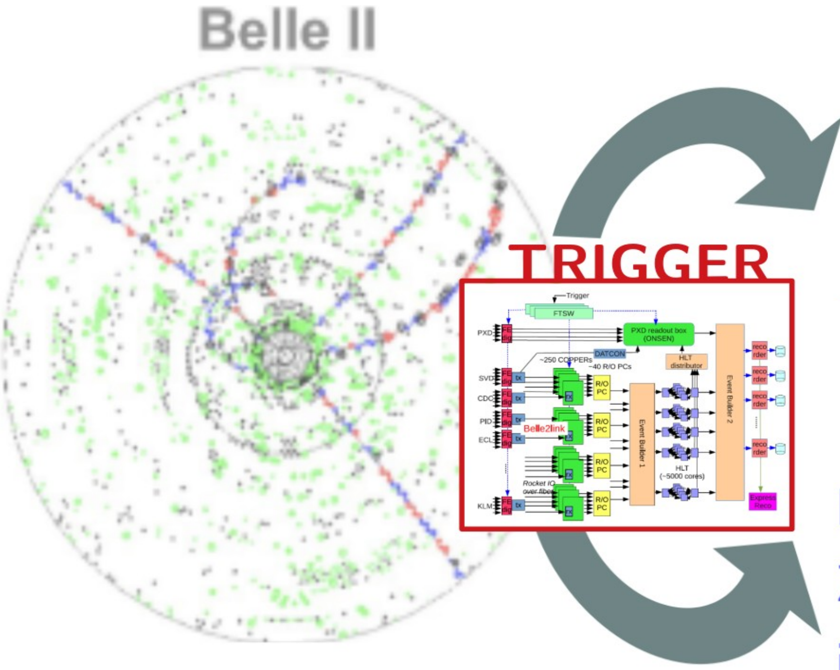
Bump hunt in M_{l+l-}

$$E_{beam} - E_{reco} = E_{miss}\ (E_{inv})$$

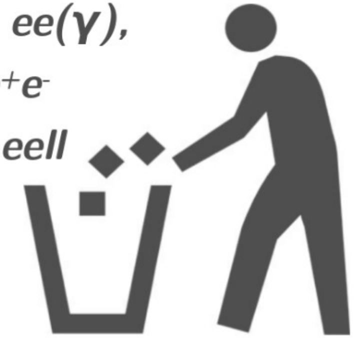
Main experimental requirements: triggers

- Specific **low-multiplicity triggers:** single track/muon/photon (previously not available at Belle)

  GOAL: suppress high-cross section QED processes O(1-300 nb), without killing the signal < O(10 fb)

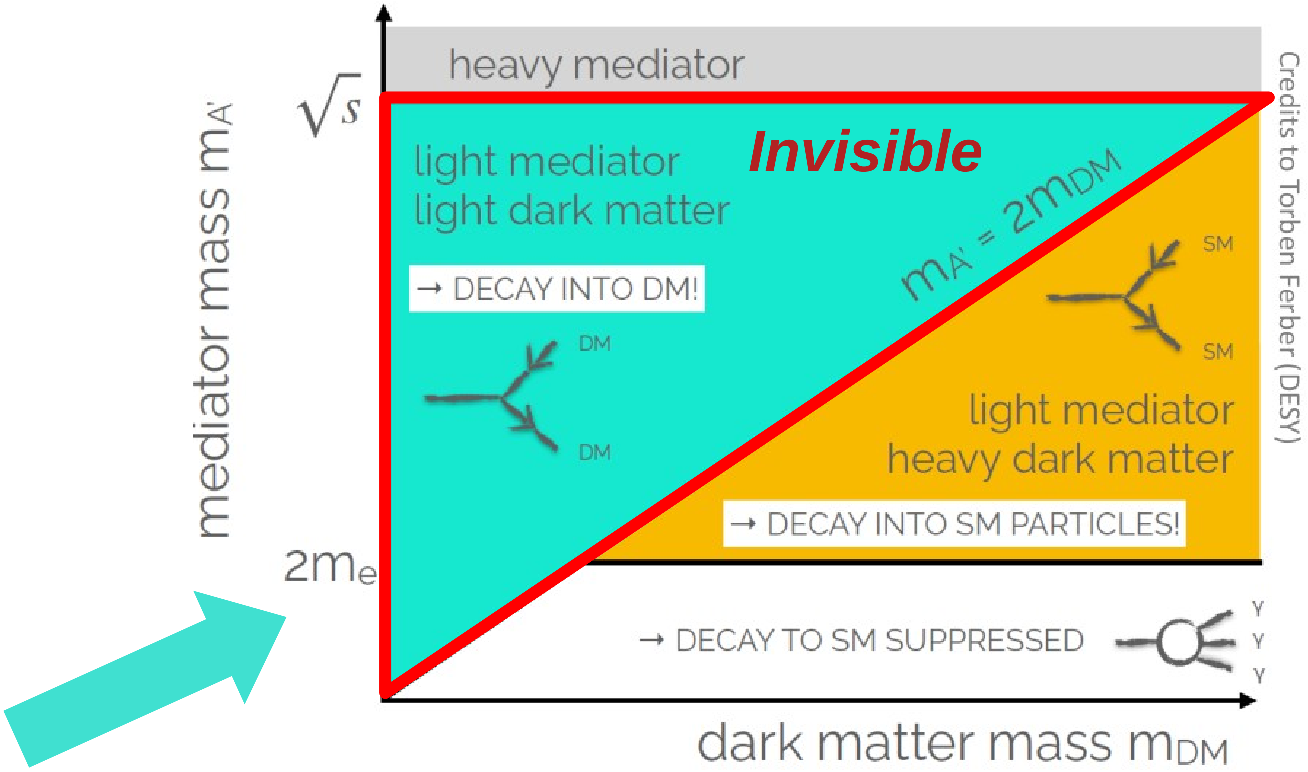


SM QED: $e^+e^- \to ee(\gamma)$, $e^+e^- \to \mu\mu(\gamma)$, $e^+e^- \to \tau\tau(\gamma)$, $e^+e^- \to eell$



NEW PHYSICS: Z' , A'→ ll, A' → invisible , a → γγ

Searches for invisible decays of new mediators



Credits to Torben Ferber (DESY)

Example:
Z' → invisible (2018)

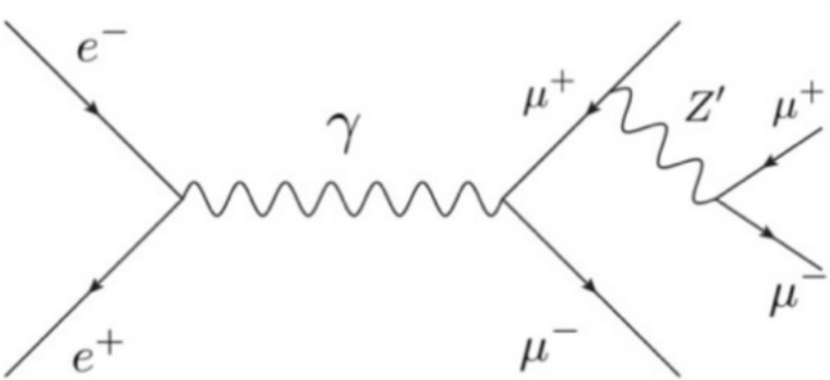
- Z' → invisible
- Dark higgstrahlung
- Single photon search

Why shall we look for an invisible Z'?

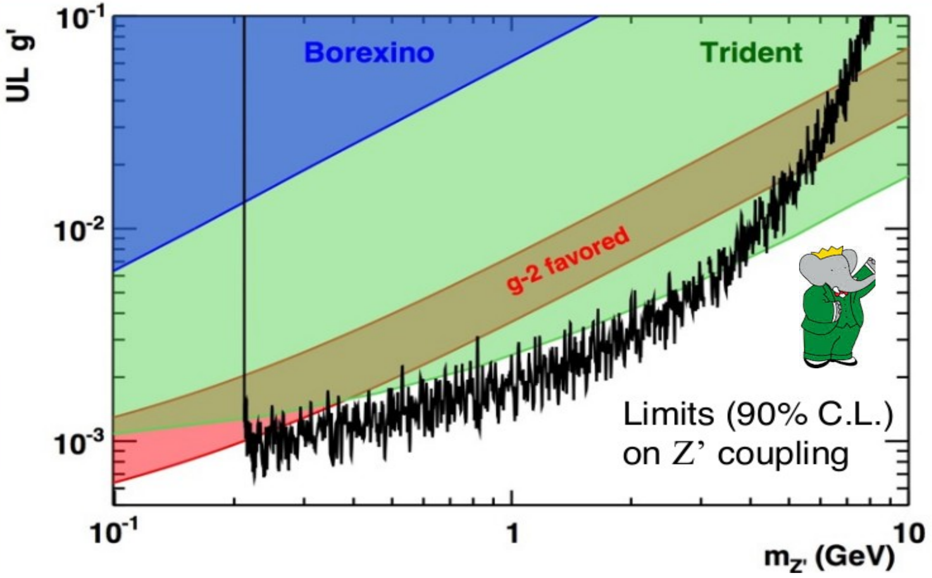
Example:
Z' → invisible (2018)

Muonic dark forces

- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ symmetry): $\mathcal{L} = \sum_\ell \theta g' \bar{\ell}\gamma^\mu Z'_\mu \ell$
  - ***If lighter accessible DM exists, Z' could decay to DM***
  - ***May explain: DM abundance, $(g\text{-}2)_\mu$ and flavor anomalies***
- Search for the process: $e^+e^- \to \mu^+\mu^- Z'$



Phase space for $m_{Z'} < 2m_\mu$ UNEXPLORED

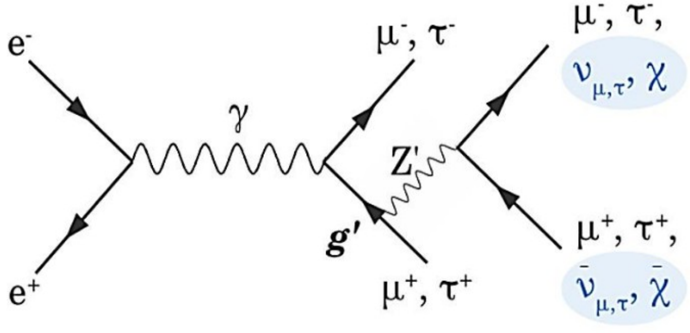


Limits (90% C.L.) on Z' coupling

Example:
Z' → invisible (2018)

Search for Z' to invisible

- Invisible signature investigated for the first time: $e^+e^- \to \mu^+\mu^- Z', Z' \to invisible$
- Search for a peak in the mass spectrum of the recoil against a $\mu^+\mu^-$ pair in events where NOTHING else is detected.



$e^+e^- \to \mu^+\mu^- + missing\ energy$

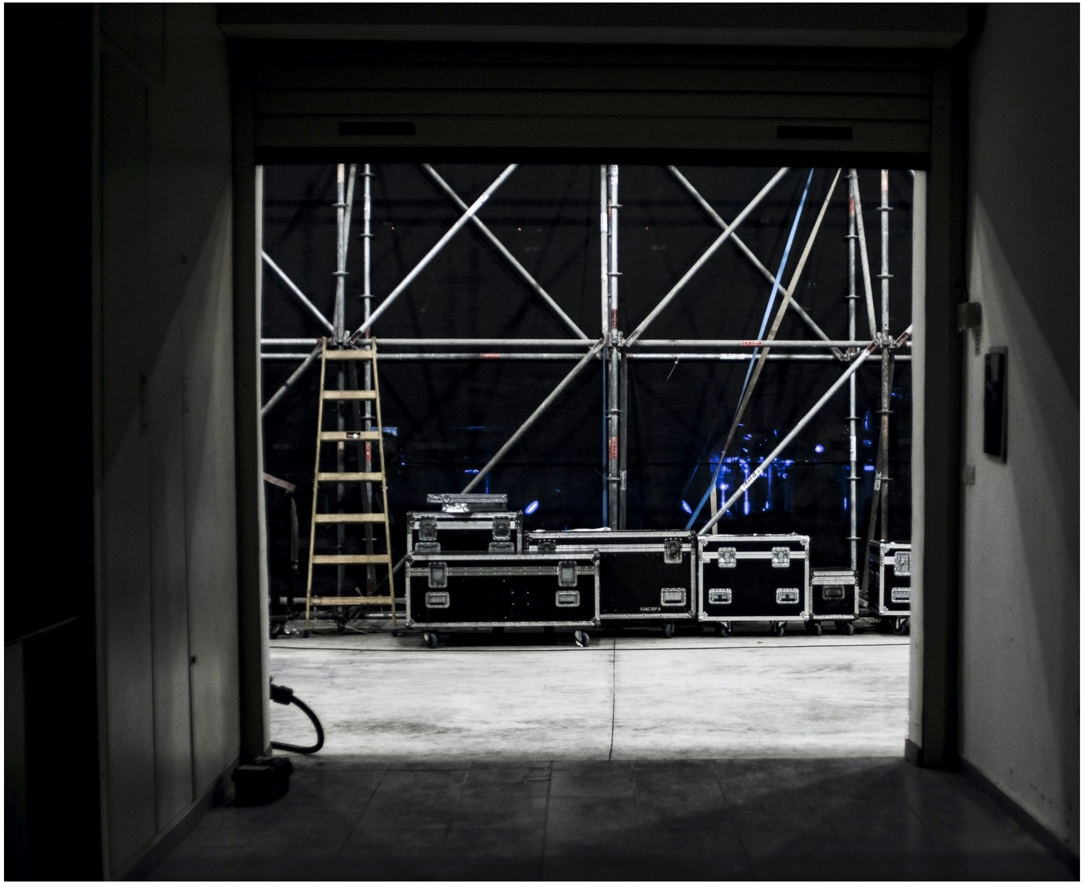
Branching ratios:

$$M_{Z'} < 2M_\mu \to \Gamma(Z' \to \text{inv.}) = 1$$
$$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/2$$
$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/3$$

Shuve et al.
[arXiv:1403.2727]
Altmannshofer et al.
[arXiv:1609.04026]

- If lighter DM is accessible ($m_\chi < m_{A'}/2$), BR($Z' \to \chi\bar{\chi}$) = 1 and SM final states are highly suppressed.

Backstage: building the analysis performance



Trailer: the plot

Models
that motivate it

Experiment features:
Trigger, detector coverage
and efficiencies

data

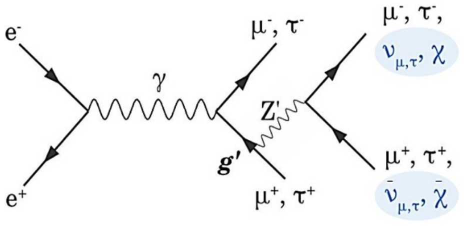
simulation

Process
to search

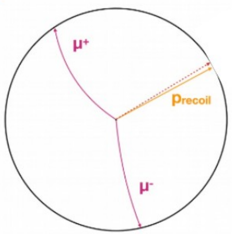
Experimental
signature

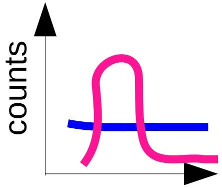
Analysis machinery:
- Event reconstruction
- Signal/Bkg discrimination (ε_{sig})
- Data validation ($\delta_{data/MC}$)
- Signal yield extraction
- Results computation

Results



$e^+e^- \to \mu^+\mu^- + missing\ energy$





Reinterpreted
within different framework
- constrain phase space parameters (set limits)
- exclude models

Example:
Z' → invisible (2018)

Analysis overview

BLIND ANALYSIS: the recoil mass spectrum is kept hidden until the finalization of the analysis procedure to prevent experimenters' bias.

Observable:

$$M^2_{rec} = s + M^2_{\mu^+\mu^-} - 2\sqrt{s}(E^*_{\mu^+} + E^*_{\mu^-})$$

$$M_{rec} = \sqrt{M^2_{rec}}, \quad \text{if } M^2_{rec} > 0;$$

$$M_{rec} = -\sqrt{-M^2_{rec}}, \quad \text{if } M^2_{rec} < 0.$$

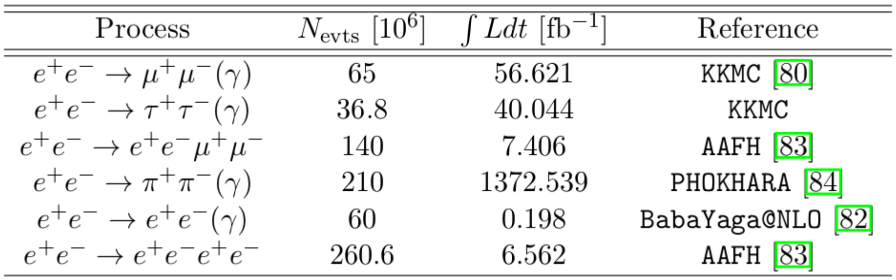
1) **Event Selection**: reconstruct the recoil against two muon tracks in events where nothing else is detected
2) **Background suppression and analysis optimization**: general selections against radiative QED processes + dedicated suppression procedure for $e^+e^- \to \tau^+\tau^- (\gamma)$ events
3) **Signal study:** extract the width of the simulated signal peak and compare to recoil mass resolution measured on data
4) **Data validation:** results on simulation must be compared to data, using signal-free control samples to avoid any unintentional *unblinding*
5) **Detector performance studies**: compute efficiencies on data and assign systematic uncertainties
6) **Signal yield extraction** by applying a Poisson counting experiment technique per each recoil mass bin and **upper limits computation** in a Bayesian approach

UNBOXED: look at observable in data!

Example:
Z' → invisible (2018)

Data sets

- Use large simulated Monte Carlo (MC) samples for:
  - compute **signal efficiency** and **expected yields**



Process	N_{evts} $[10^6]$	$\int L dt$ $[\text{fb}^{-1}]$	Reference
$e^+e^- \to \mu^+\mu^-(\gamma)$	65	56.621	`KKMC` [80]
$e^+e^- \to \tau^+\tau^-(\gamma)$	36.8	40.044	`KKMC`
$e^+e^- \to e^+e^-\mu^+\mu^-$	140	7.406	`AAFH` [83]
$e^+e^- \to \pi^+\pi^-(\gamma)$	210	1372.539	`PHOKHARA` [84]
$e^+e^- \to e^+e^-(\gamma)$	60	0.198	`BabaYaga@NLO` [82]
$e^+e^- \to e^+e^-e^+e^-$	260.6	6.562	`AAFH` [83]

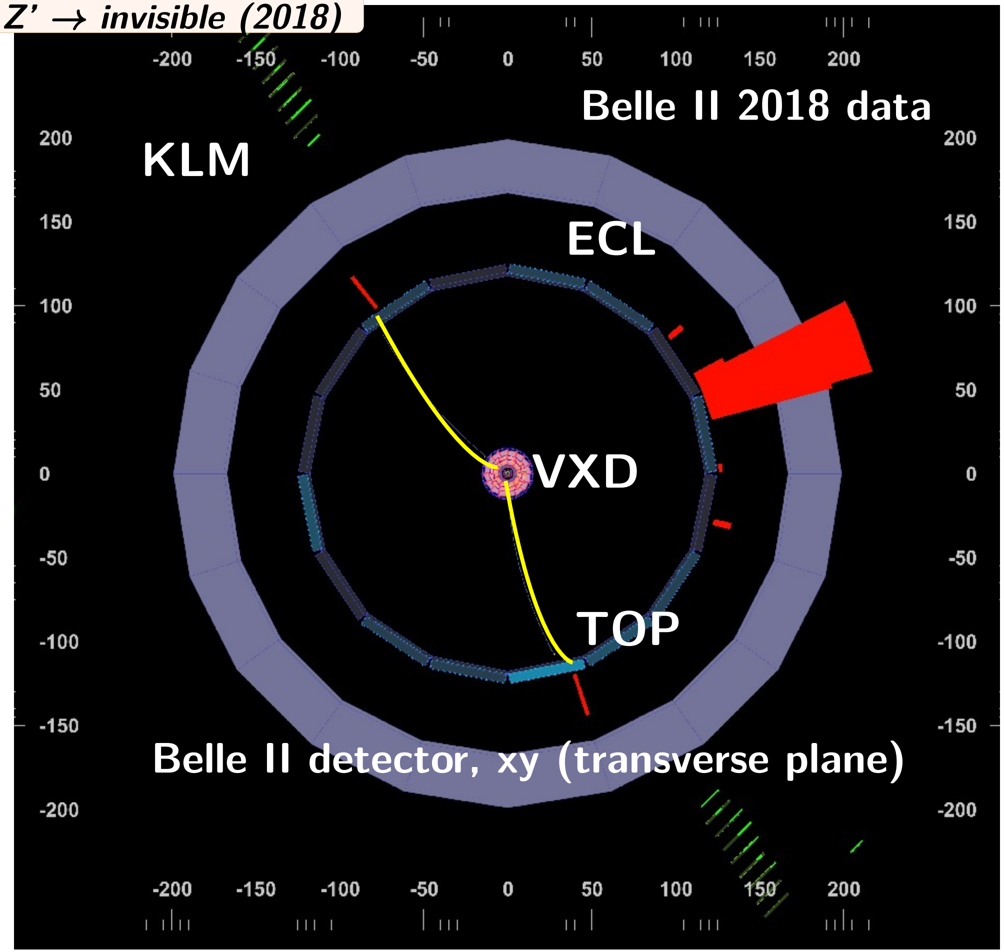
→ Simulate also signal processes, with dedicated generator (**MadGraph5)**

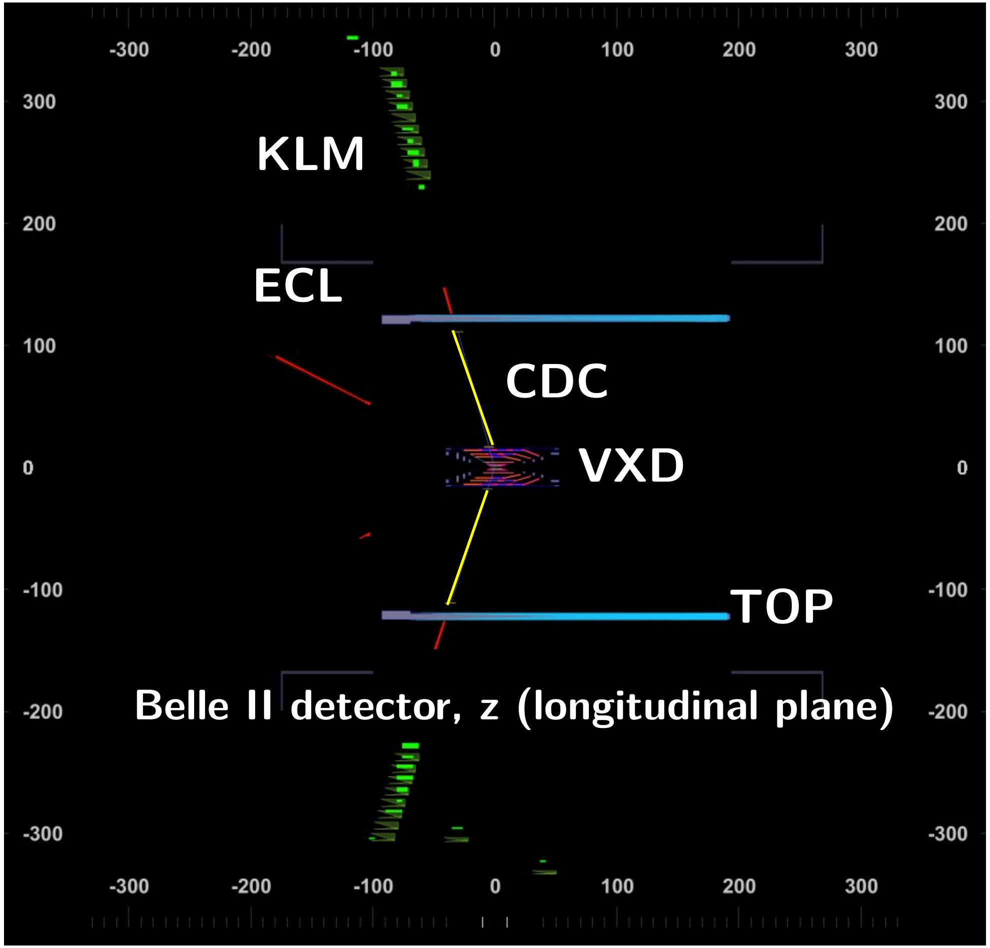
- Actual data needed to:
  - **validate** the analysis procedure
  - measure detector efficiencies and **systematic uncertainties**
  - extract the **final results** (by comparing yields in data to expected)

→ CAVEAT: simulation might be missing/ incomplete, mis-model the data
→ Some detector effect not simulated

How would a dimuon event look like?
Exploit the “event display”...

Example:
Z' → invisible (2018)

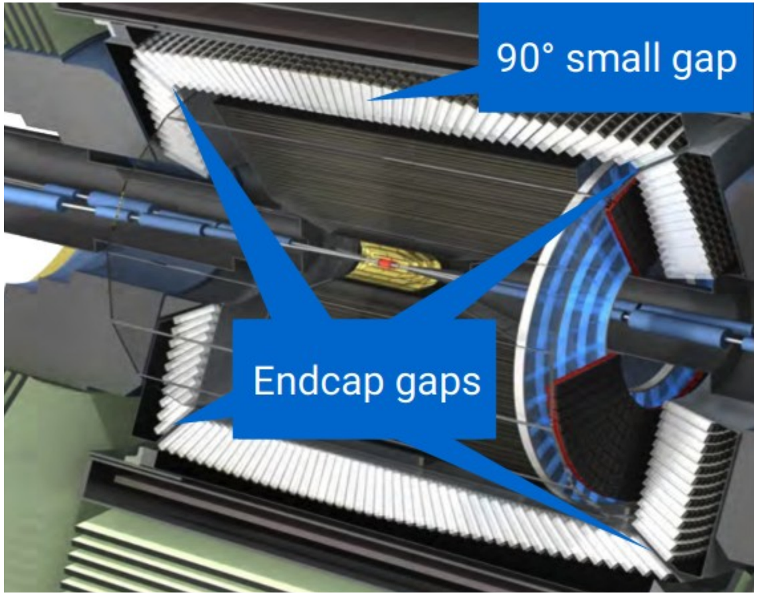




Example:
Z’ → invisible (2018)

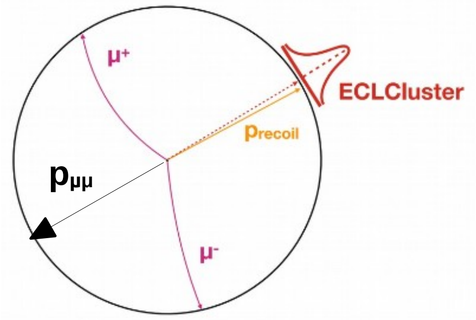
Event selection

Signature: “peak in the recoil against a $\mu^+\mu^-$ pair in events…



Apply **experimental requirements** and constraints

- Two tracks from the interaction consistent with muons → *dimuon candidate*, within fiducial ECL barrel region
- CDC **trigger** line fired in data and mimic the trigger selection in simulation



…where **nothing** else is detected”

- no ECL cluster within 15° cone with respect to the reconstructed recoil momentum *(closest photon veto)*
- no reconstructed π^0 candidate = {two photons with invariant mass in the range of known pion mass [125-145] MeV} *(π^0 veto)*
- no energy deposited in the ROE *(extra energy veto)*

Example:
Z' → invisible (2018)

Background rejection

Background from QED processes that can mimic the final state of two muons + missing momentum because of acceptance or undetected particles:

1) Identify background source and study signal features

2) Devise a method to optimally discriminate:

→ cut-based or multivariate methods; figure of merit;...

- $e^+e^- \to \mu^+\mu^-(\gamma)$,
- $e^+e^- \to \tau^+\tau^-(\gamma)$, $\tau \to \mu\nu\nu$
- $e^+e^- \to \mu^+\mu^-e^+e^-$

- affects the low mass range $M_{rec} < 3$ GeV
- **Dominant contribution in the recoil mass range ~ 3-7 GeV**
- Affects high mass spectrum $M_{rec} > 7$ GeV where sensitivity is also limited by the decreasing production cross section (1/s)

- Selections optimization by maximizing the *Punzi figure of merit* in each recoil mass bin.

$FOM_{Punzi} = \varepsilon/(a/2 + \sqrt{B})$, a=1.64 (90% CL)

- Number of surviving events and signal efficiencies computed for each recoil mass bin

→ Evaluate the selection performance on simulation

Example:

Z' → invisible (2018)

Data validation

- Impact of the selections studied on **signal-free control samples** in data and simulation:

ee sample: Bhabha events, ττ (τ→ e) pairs

→ revert muon selection

- check τ pair background ($3 < M_{rec} < 7$ GeV)

***μμγ, eeγ, eμγ samples: r*adiative dilepton events**

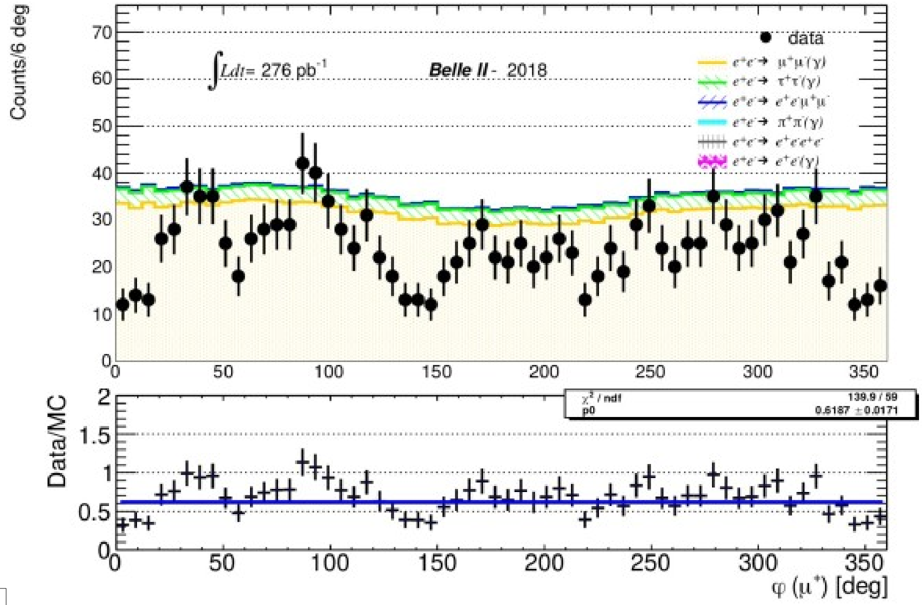
- check low recoil mass region, $M_{rec} < 3$ GeV
- validate the trigger selection

→ revert photon veto

***μμ, eμ samples* with reversed bkg-suppression procedure**

- analogous to the background expected in signal regions
- assign a systematic uncertainty on the expected background level

→ revert bkg rejection



→ validate performance on data: check data/simulation agreement, extract corrections and systematic uncertainties

Example:

Z' → invisible (2018)

Systematic uncertainties

Extract from data, uncertainty due to the statistical model (Poisson counting experiment)

$$\sigma_{Z'} = \frac{N_{\rm obs} - B_{\rm exp}}{L \times \epsilon_{\rm sig}}$$

Estimated from simulation

From other measurement

Example:
$Z' \to$ invisible (2018)

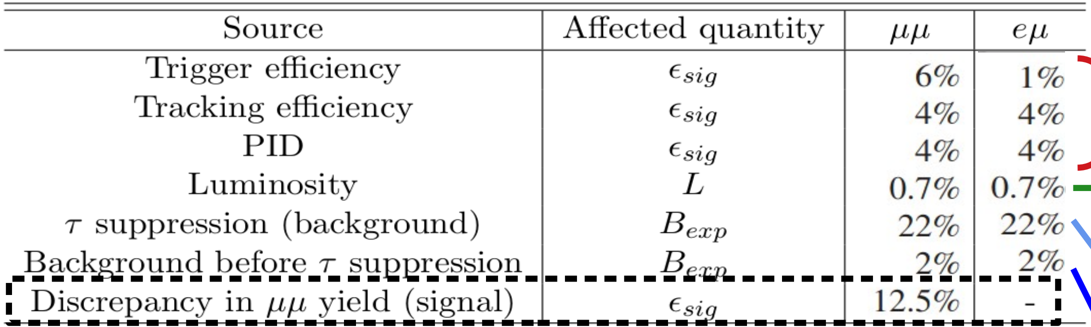
Systematic uncertainties

Extract from data, uncertainty due to the statistical model (Poisson counting experiment)

$$\sigma_{Z'} = \frac{N_{\text{obs}} - B_{\text{exp}}}{L \times \epsilon_{\text{sig}}}$$

From other measurement

Estimated from simulation



Source	Affected quantity	$\mu\mu$	$e\mu$
Trigger efficiency	ϵ_{sig}	6%	1%
Tracking efficiency	ϵ_{sig}	4%	4%
PID	ϵ_{sig}	4%	4%
Luminosity	L	0.7%	0.7%
τ suppression (background)	B_{exp}	22%	22%
Background before τ suppression	B_{exp}	2%	2%
Discrepancy in $\mu\mu$ yield (signal)	ϵ_{sig}	12.5%	-

- From measured data-MC discrepancy, not associated to any known source, as systematic uncertainty in the **signal efficiency.**

- ✓ Trigger, Tracking and Particle ID: from performance studies
- ✓ from offline luminosity measurement [arXiv:1910.05365]
- ✓ Bkg suppression impact on control sample (statistically dominated)
- ✓ Background yields: from data-MC agreement in control samples with reversed τ-suppression selection

Example:
Z' → invisible (2018)

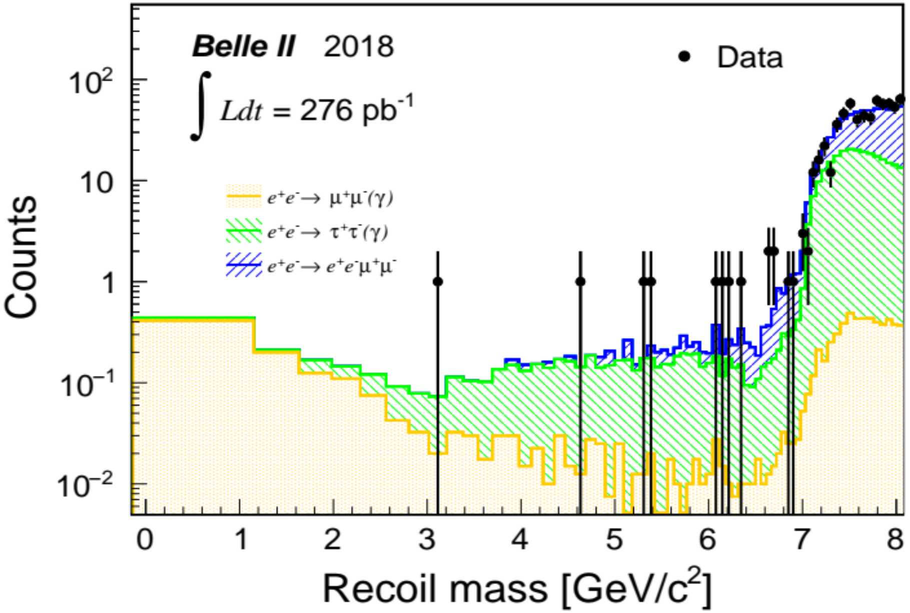
- Selection finalized
- Corrections applied and systematic uncertainties assessed from cross-check on control sample/sidebands
- Signal yield extraction and limits computation defined

Time to unboxed the data and compute the results!

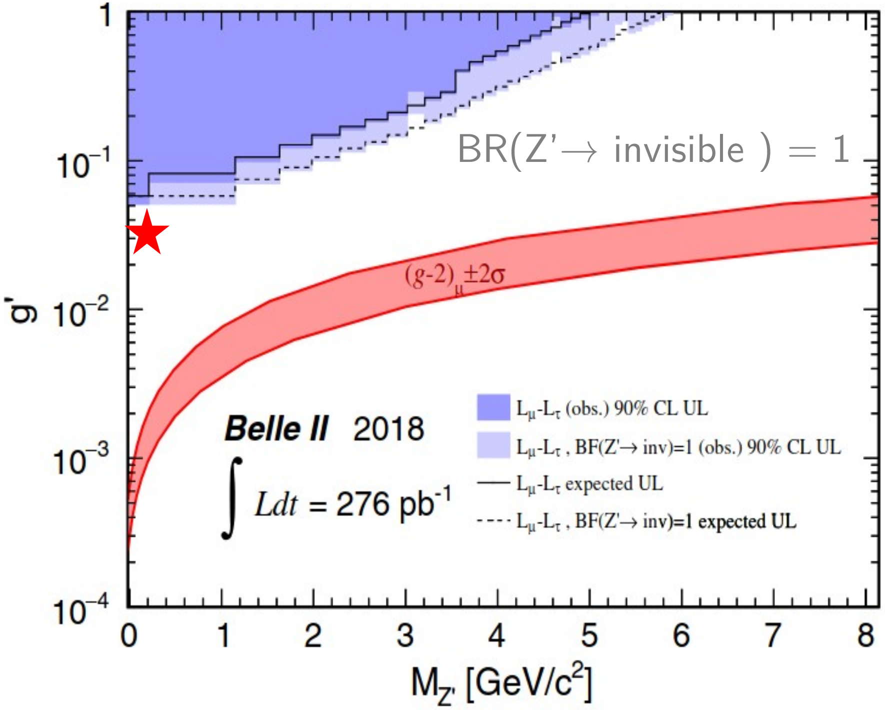
Example:
Z' → invisible (2018)

Le grand final: unboxed results

- **Signal yields** extracted by applying a **Poisson counting experiment** technique, in each recoil mass bin, after the final selections → **upper limits** on the cross-section $\sigma_{Z'}$ are computed in a Bayesian approach



Phys. Rev. Lett. 124, 141801



★ First upper limits at 90% CL on g' for $M_{Z'} < 2m_\mu$

Return to the present…

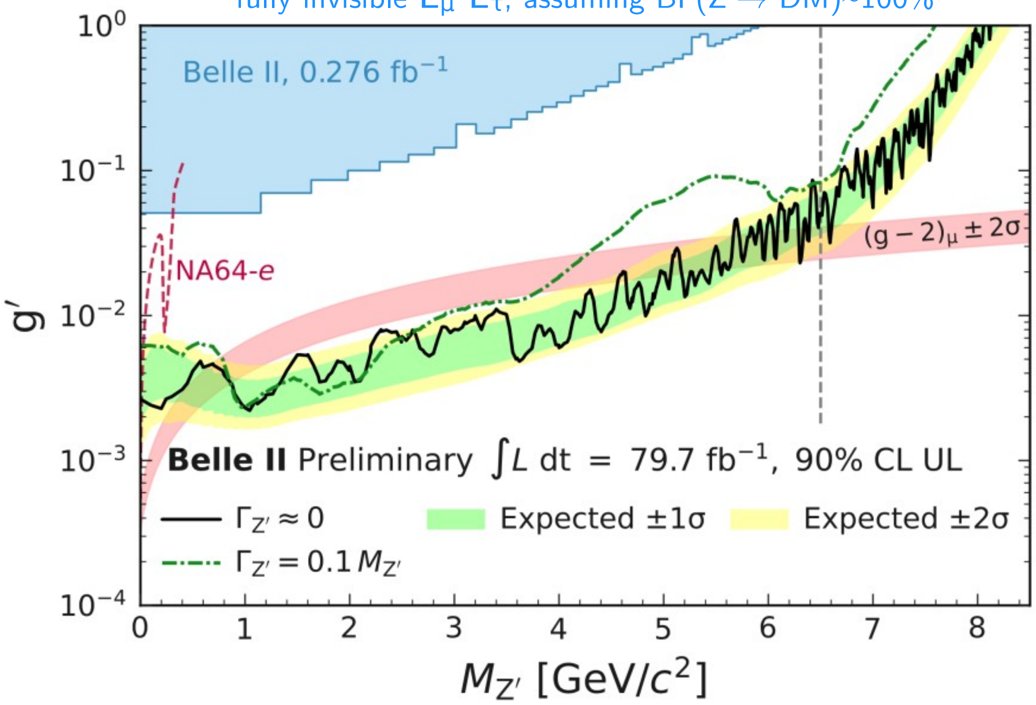
New limits on invisible Z’

Several updates since 2019:

- Much higher luminosity (~ x 300)
- Analysis improvements
  - Better particle identification (muon ID)
  - Better background suppression algorithm (MVA)
  - Frequentist approach for UL extraction based on fitting
- New trigger lines (devised after the pilot run)

- Template **fits** to the recoil mass squared, in bins of recoil polar angle → no significant excess, 90% CL upper limits on the ***coupling constant g’***

fully invisible L_μ-L_τ, assuming BF(Z’→ DM)~100%

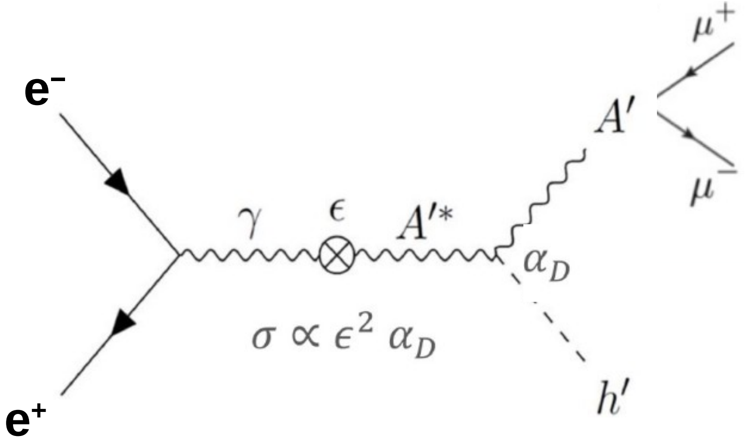


IMPROVEMENT: $(g\text{-}2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5$

Inheriting from Z’ → invisible search to expand to other cases: dark higgsstrahlung

Dark higgsstrahlung

- Dark photon (A') mass can be generated via a spontaneous symmetry breaking(*) mechanism, by adding a dark Higgs boson (h')
- *Look for the dark Higgsstrahlung* process, $\mathbf{e^+e^- \rightarrow A'^* \rightarrow h' \, A'}$

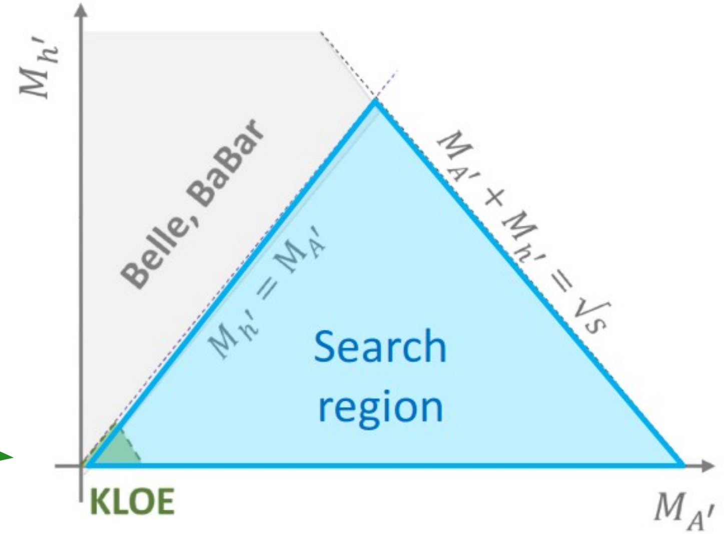


- 4 parameters (no mixing with SM Higgs assumed): $\boldsymbol{m_{h'}}$, $\boldsymbol{m_{A'}}$, **ε, α**$_D$
- $M_{h'} > M_{A'}$: *h' can decay to a pair A', and A' into SM final states, "visible dark higgs" already searched by Belle, Babar*
- $M_{h'} < M_{A'}$: ***invisible** decays of h'*

* Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

Invisible dark higgsstrahlung

- Belle II has unique capability to probe the ***invisible h' decay ($m_{h'} < m_{A'}$)*** with A' decaying to a muon pair
- Previously constrained only by **KLOE**[(*)]



- Same signature of two muon + missing momentum for the Z' search
  - Expected similar background contributions

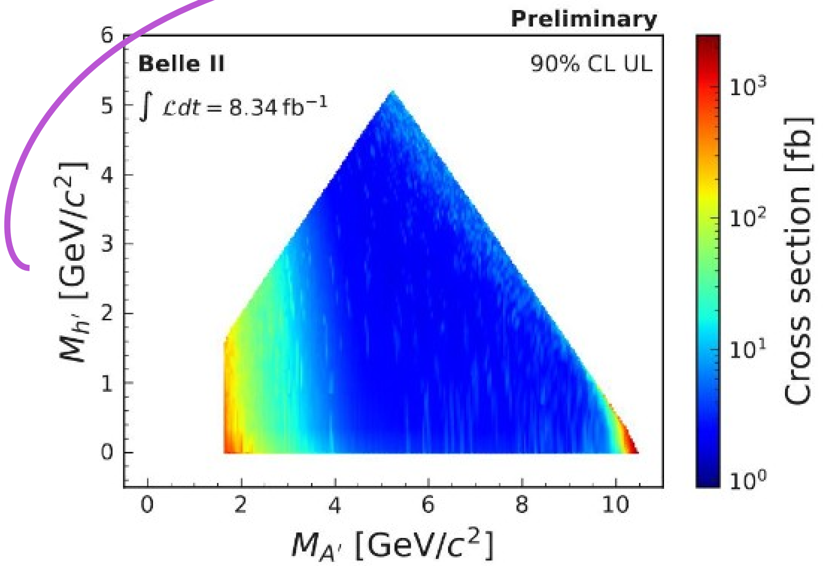
Use also direct mass $M_{\mu\mu}$ → expected to peak at A' mass

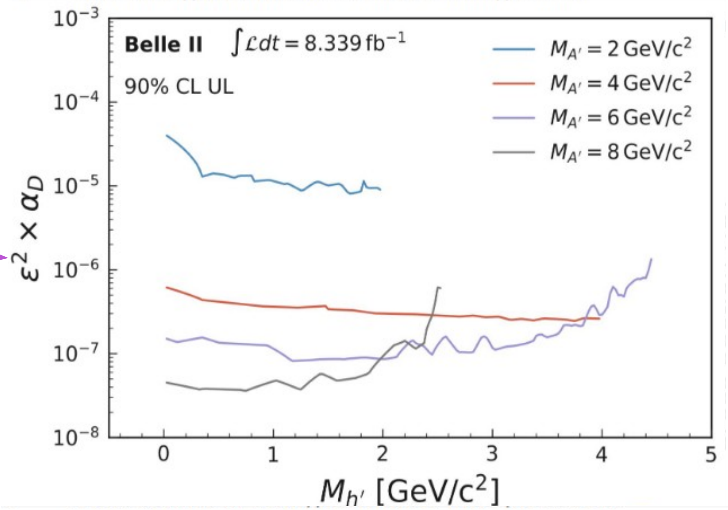
- 2D plane search ($M_{\mu\mu}$, M_{rec})

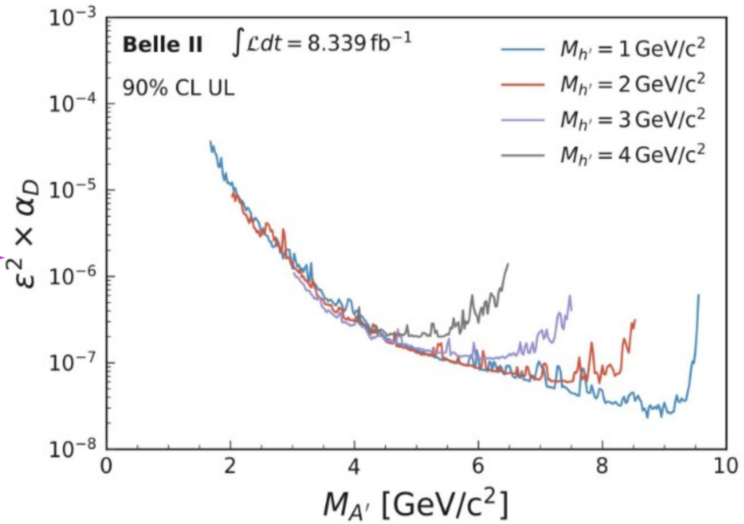
* Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

Dark higgsstrahlung results

- No significant excess, set 90% CL upper limits → **probe non-trivial $\varepsilon^2\alpha_D$ couplings**







World leading results for $1.65 < M_{A'} < 10.51$ GeV/c^2

→ can be interpreted in a wider class of theoretical models

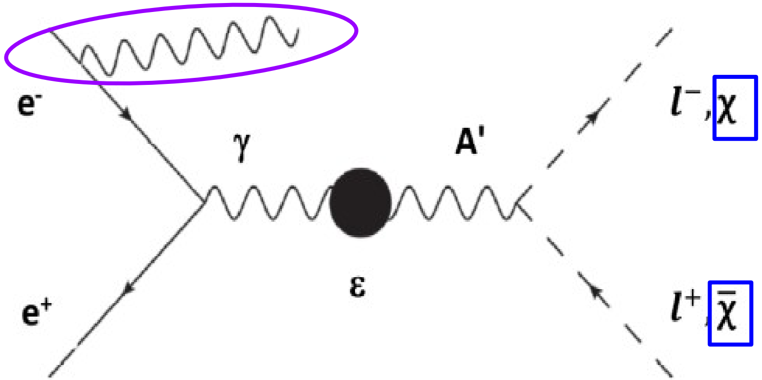
(e.g., long-lived higgs mixing with h_{SM})

Searching for invisible decays of dark photon: mono-photon search

Single photon search

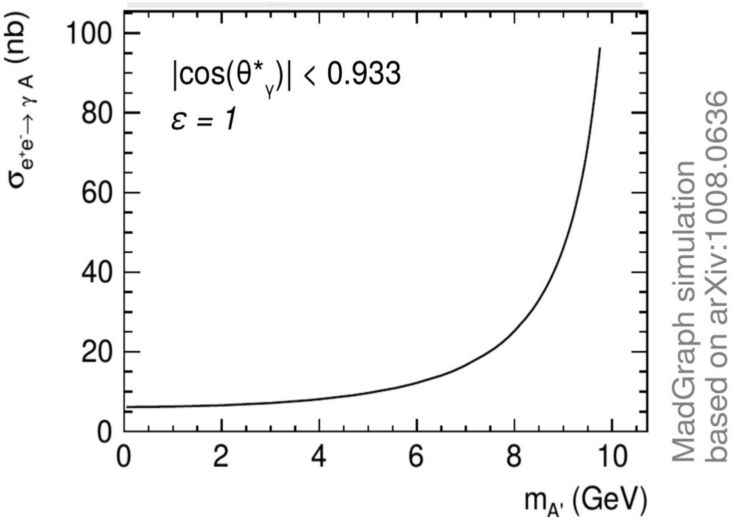
- At e^+e^- colliders investigate the ISR production $e^+e^- \to \gamma A'$.

$m_{A'} > 2m_\chi$ → A' decays 100% invisibly into ***DM particle***



$$\mathcal{L} \supset \varepsilon A'_\mu J^\mu_{\mathrm{SM}}$$

Batell et al. (2009), arXiv:0903.0363



MadGraph simulation based on arXiv:1008.0636

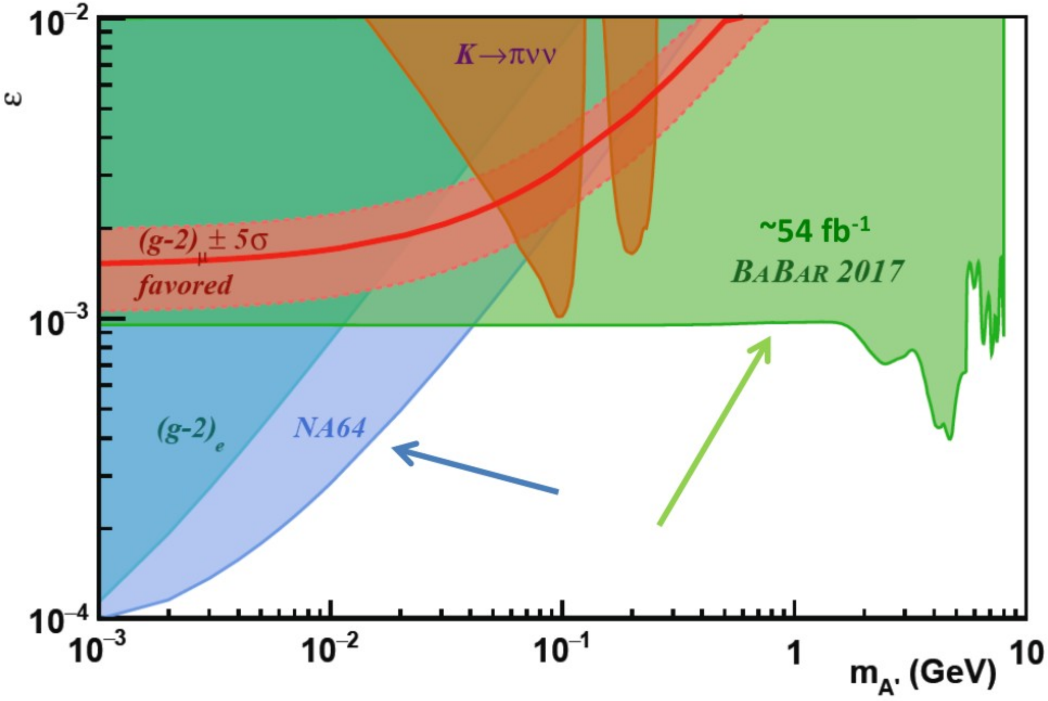
- Select events with **nothing** but a single high energetic *ISR photon.* Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

(First and) simplest dark sector to search for, but experimentally very challenging!

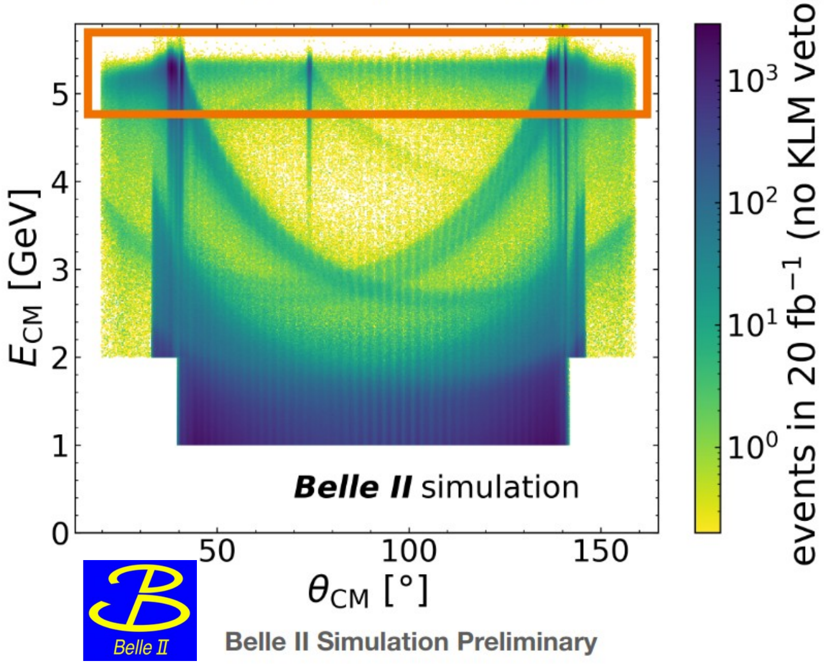
- Dedicated **single photon** trigger, not available at Belle and only on 10% of Babar data

Single photon search

(un)holy grail

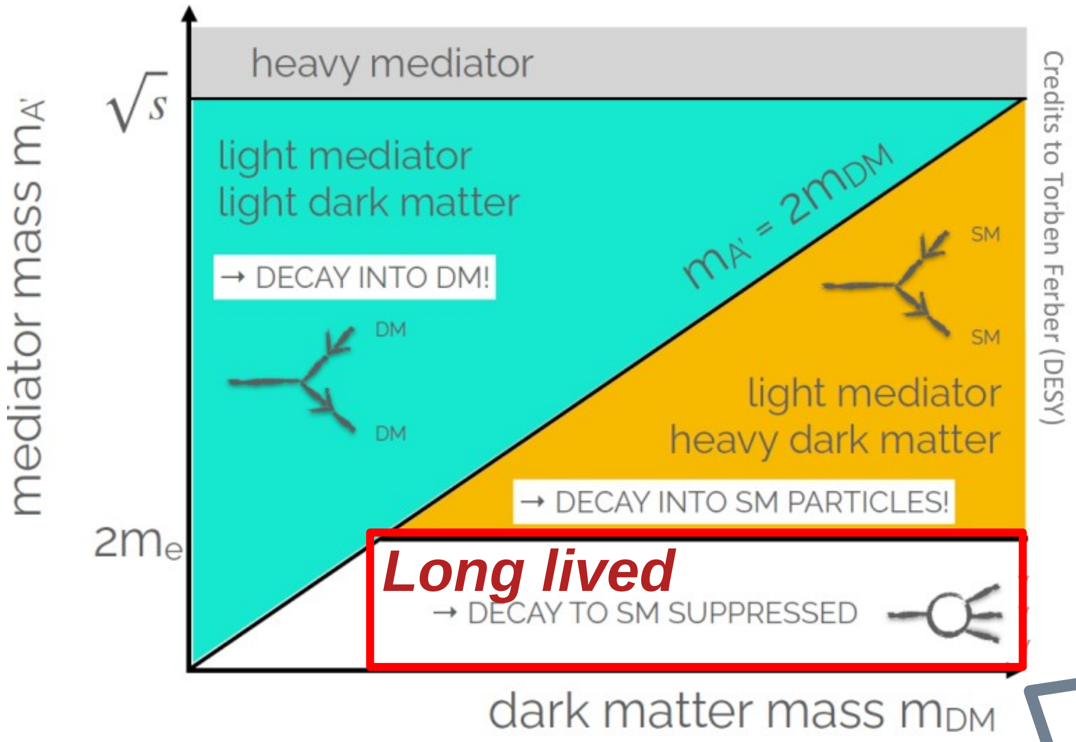


Background: QED processes $e^+e^- \to \gamma\gamma(\gamma)$ *(low mass region)* and radiative Bhabha $e^+e^- \to e^+e^- \gamma(\gamma)$ (*high mass* region) + cosmics

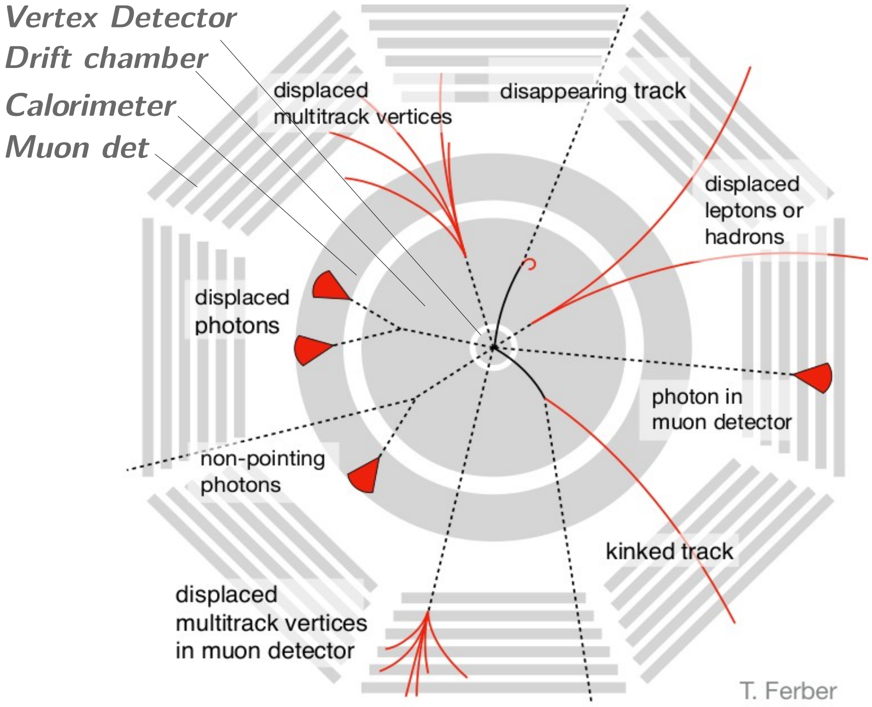


Crucial to devise photon veto to compensate for detector inefficiencies that could mimic monophoton signal

Displaced vertices at Belle II



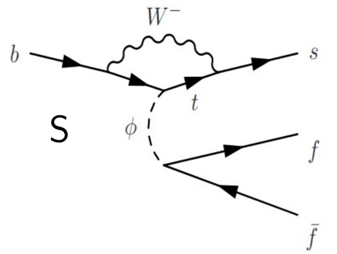
Credits to Torben Ferber (DESY)



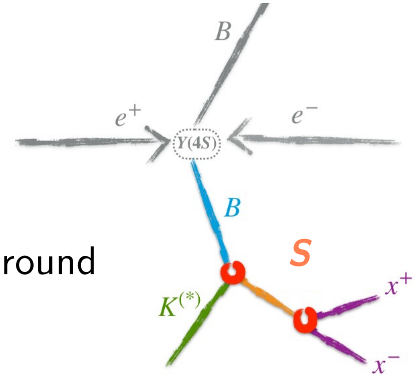
T. Ferber

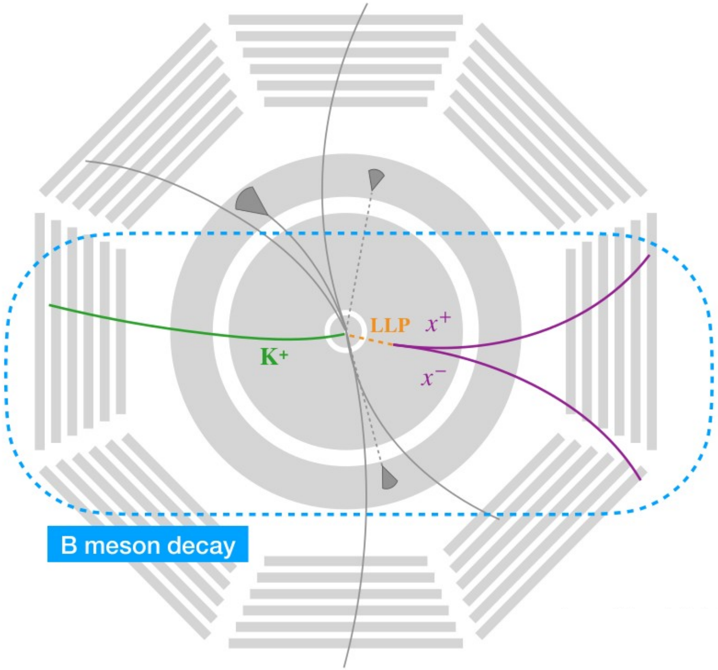
Search for long-lived (pseudo)scalar in b→s transitions

- **Model-independent** search for dark scalar particles S from B decays in rare $b \to s$ transition
  - S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for $\theta_s << 1$)
  - for $M_S < M_B$ decay to dark matter kinematically forbidden by relic density constraint

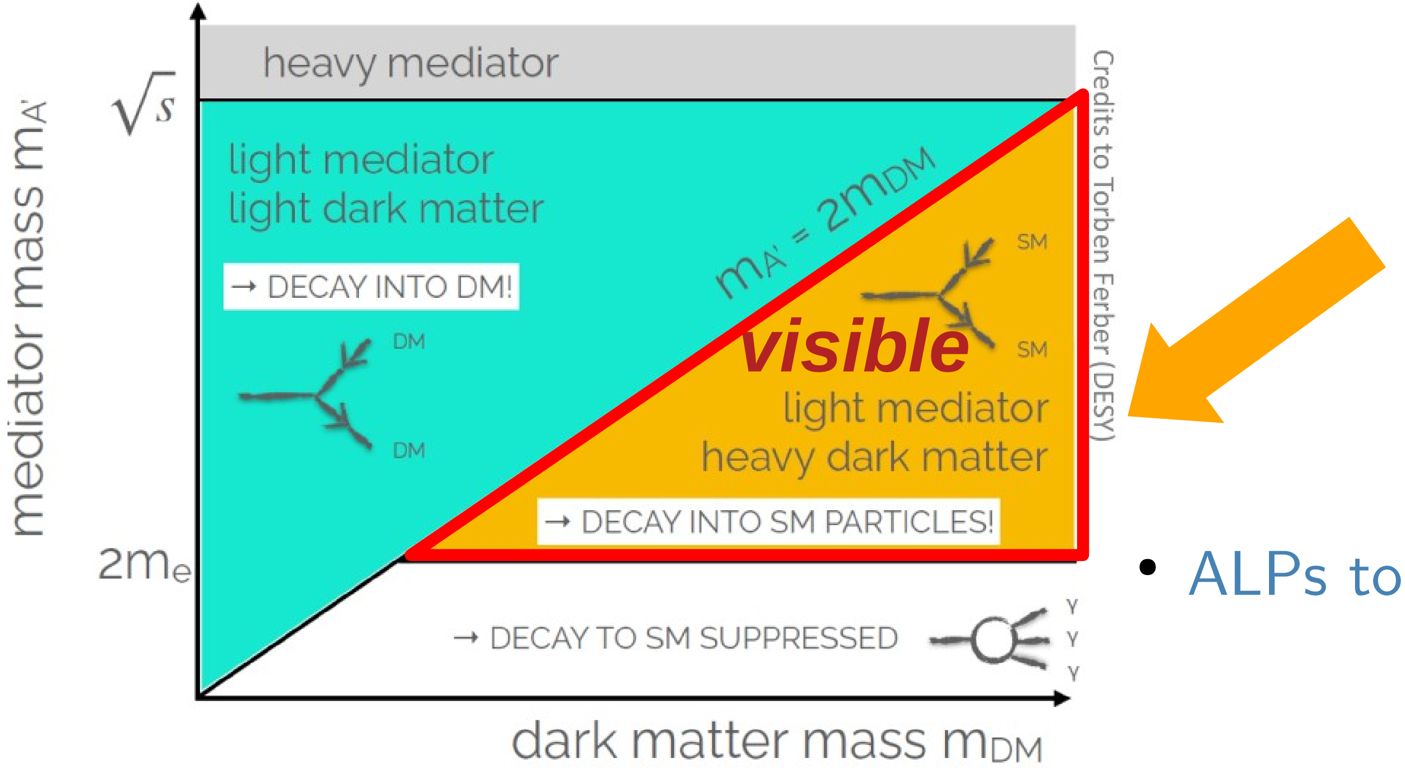


- Look for S decays into SM final states in **8 exclusive channels:**
  - $B^+ \to K^+ S$ and $B^0 \to K^{*0} (\to K^+\pi^-) S$,
    with $S \to ee/\mu\mu/\pi\pi/KK$
- B-meson kinematics to reject combinatorial background





Searches for visible decays



Credits to Torben Ferber (DESY)

- ALPs to photons

Exploring pseudo-scalar portals: ALPs

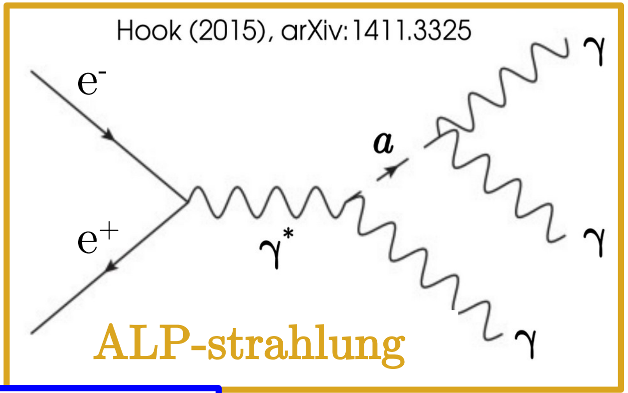
Axion-like particles

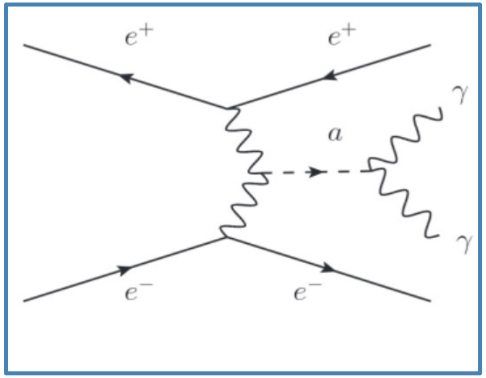
- Axion-like particles (ALPs) are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants $[g_{aV}] \sim 1/M$

- Explored photon coupling $g_{a\gamma\gamma}$ in ***ALP-strahlung* processes**

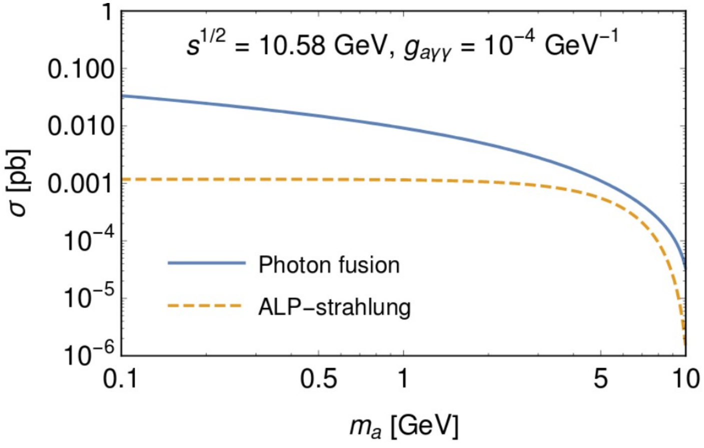
  → *photon fusion* sensitivity limited by irreducible $e^+e^- \to \gamma\gamma$ background

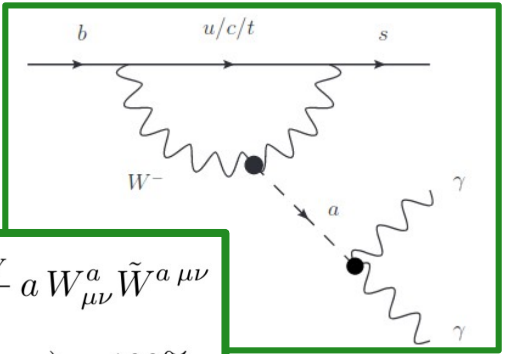
- Possible to investigate g_{aW} coupling in neutral current processes (rare B meson decays): **B→Ka**


Hook (2015), arXiv:1411.3325



$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

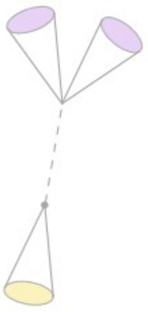




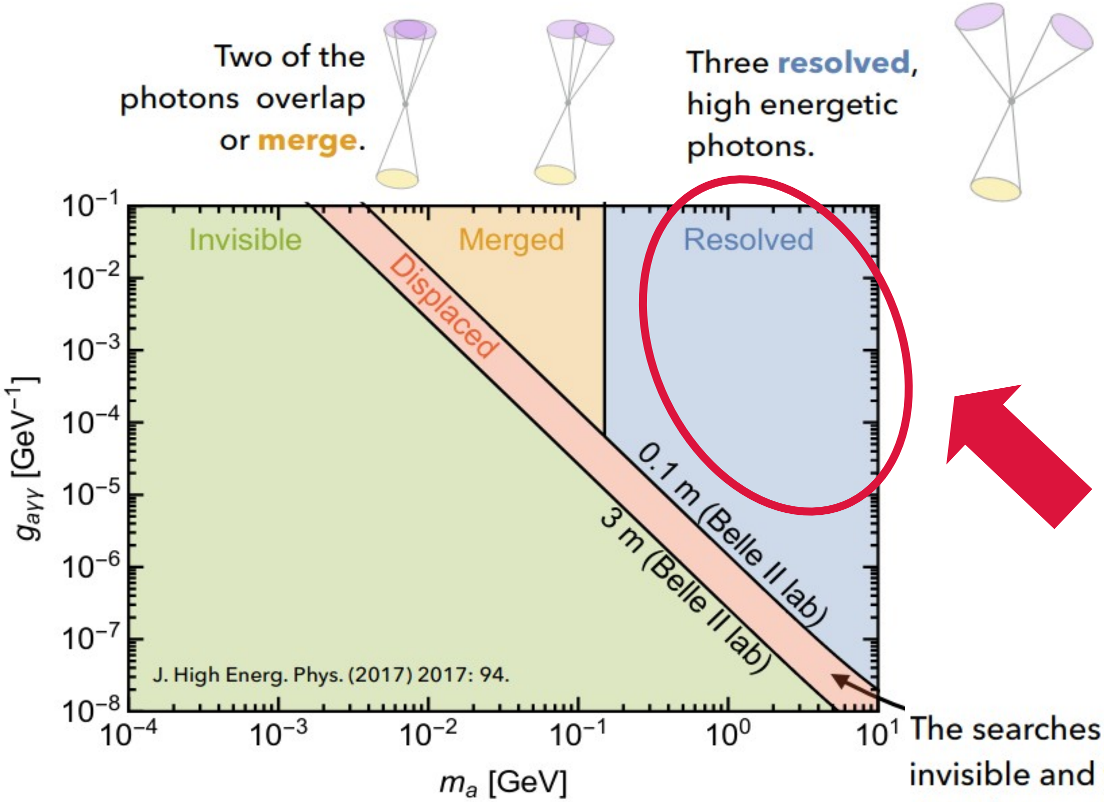
$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

$$BF(a \to \gamma\gamma) = 100\%$$

ALP-strahlung: a → γγ search



ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



Two of the photons overlap or **merge**.

Three **resolved**, high energetic photons.

J. High Energ. Phys. (2017) 2017: 94.

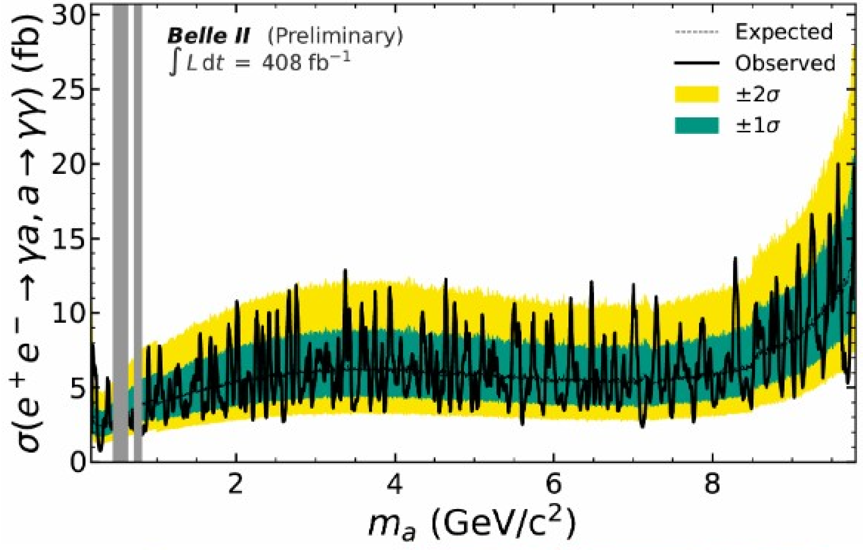
The searches for invisible and visible ALP decays veto this region.

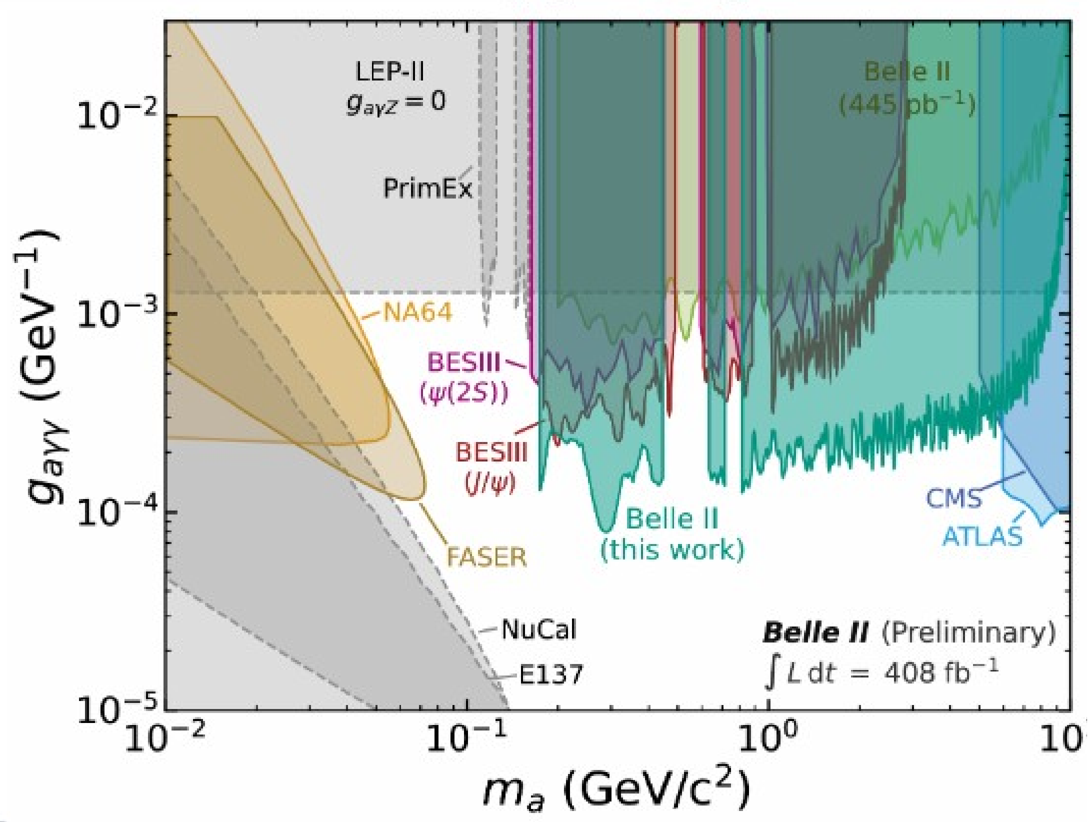
- Select fully neutral events consisting of ***3 isolated photons*** with a total invariant mass consistent with center of mass energy

a → γγ: existing limits

- Set 95% CL upper limits on $g_{a\gamma\gamma}$ coupling

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$



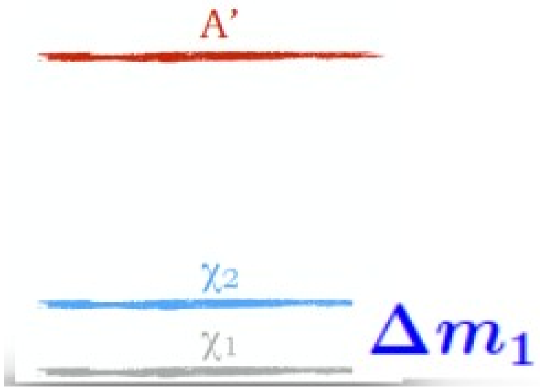


Rich dark sectors: non-minimal model testing

Inelastic dark matter

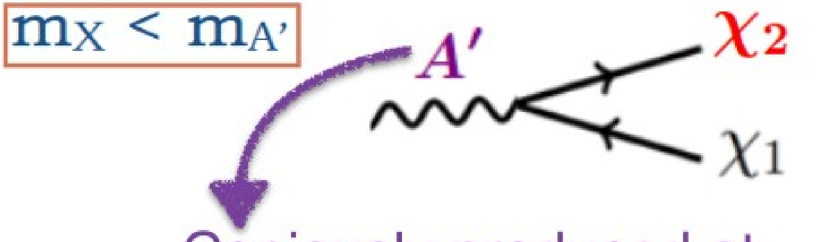
- DM models may include more particles in the dark sectors
- Inelastic dark matter (IDM) is an interesting and accessible case to look for
  - Consider two states with a small mass splitting, χ1 and χ2 and a dark photon mediator A’
    - χ1 is stable (relic)
    - χ2 is long-lived at small values of kinetic-mixing coupling ( )
- IDMs are rather hidden to direct detection experiments (also CMB constraints are relaxed)

$$\Delta \equiv \frac{m_2 - m_1}{m_1} \ll 1$$



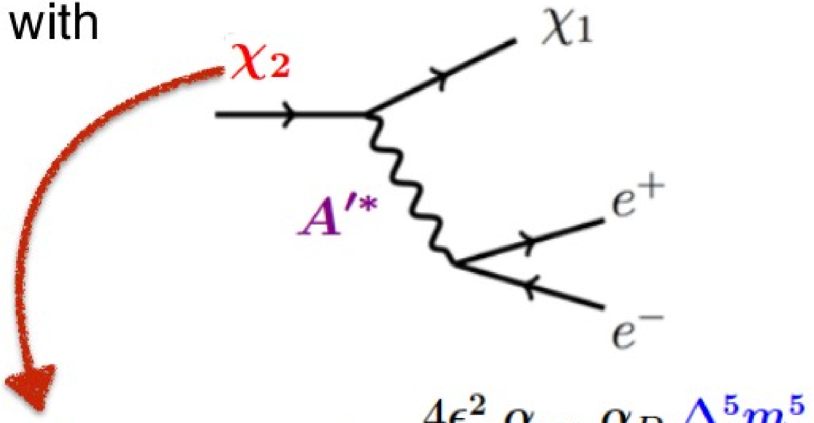
Inelastic dark matter decays

$m_\chi < m_{A'}$



Copiously produced at high intensity experiments

with



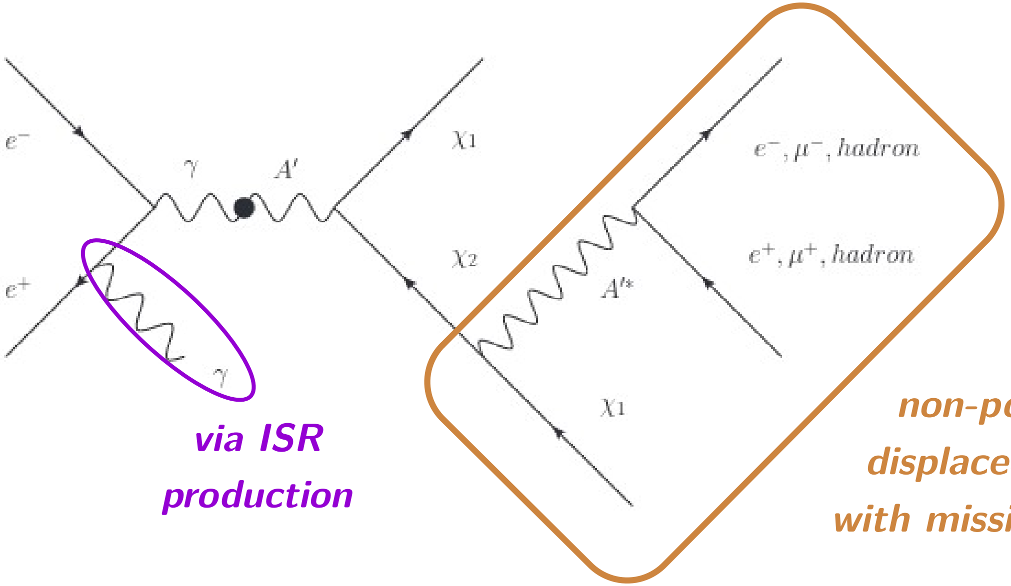
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\, \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

→ unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed

high intensity experiments are the prime avenue to probe IDM!

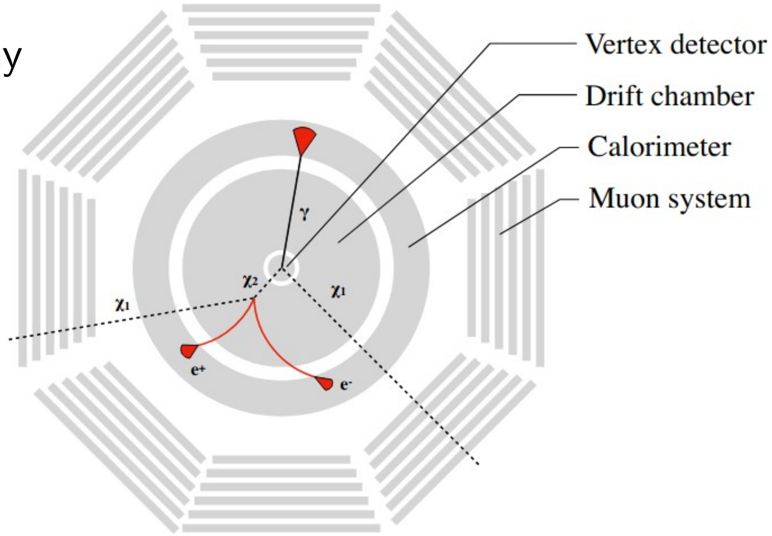
IDM signatures

- focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$, such that A'→ χ1 χ2 is dominant decay



via ISR production

non-pointing displaced vertex with missing energy



5 parameter model:
$m_{A'}$ (fixed relative to $m_{\chi 1}$)
$m_{\chi 1}$ (scan)
mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
dark coupling α_D (fixed to benchmarks)
kinetic mixing parameter ε (limit)

- ***Mandatory to implement new trigger for displaced vertex detection***
- Belle II could constrain the kinetic mixing $< 10^{-4}$

Journal of High Energy Physics volume 2020, Article number: 39 (2020)

Conclusion

- Thermal dark sectors are favored by many dark matter models, theoretically well motivated
- Compelling to search as broadly, as much model-independent as possible → Low energy, high intensity experiments are perfect testbed for thermal dark sector targets
- Electron-positron colliders have unique/world-leading reach in many searches → Important complementarity with present and future fixed-target experiments

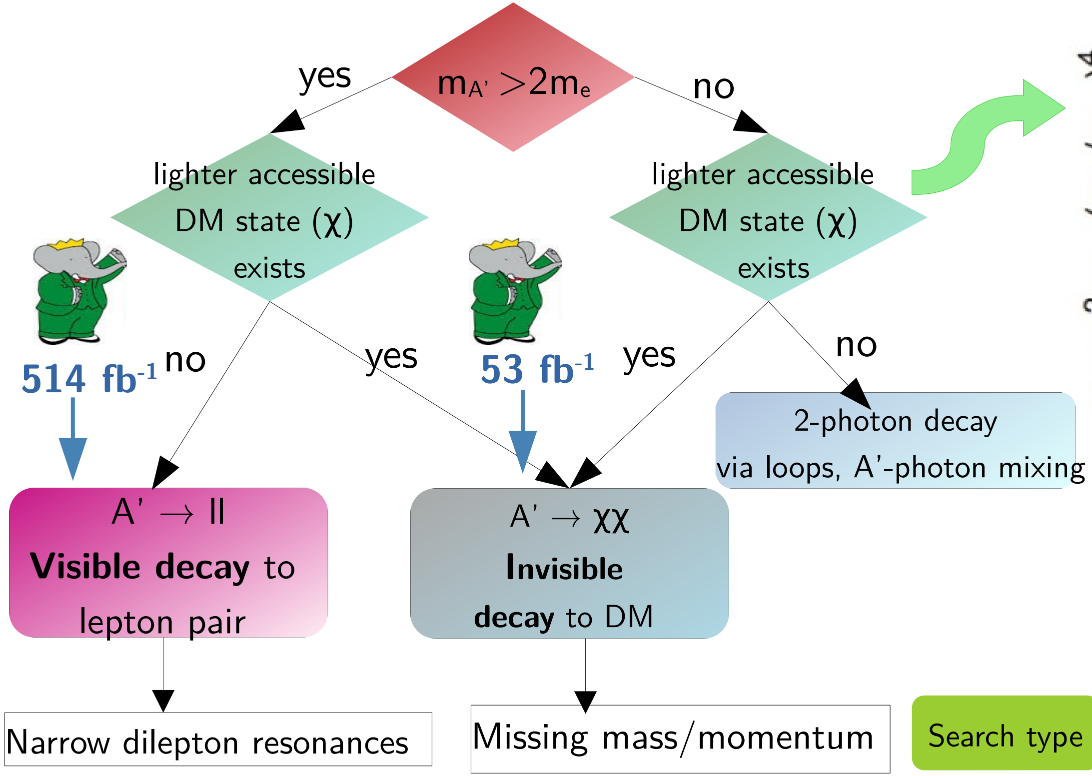
References:

- Dark Sector Studies with Neutrino Beams (Snowmass Whitepaper)
- Snowmasss 2021 RF6 Dark Sector Physics Report

- U.S. Cosmic Visions: New Ideas in Dark Matter 2017: Community Report
- The Belle II Physics Book, PTEP 2019 (2019)

Backup

Dark photon (and DM) signatures



$m_{A'} > 2m_e$

yes

no

lighter accessible DM state (χ) exists

lighter accessible DM state (χ) exists

514 fb^{-1}

no

yes

53 fb^{-1}

yes

no

2-photon decay via loops, A'-photon mixing

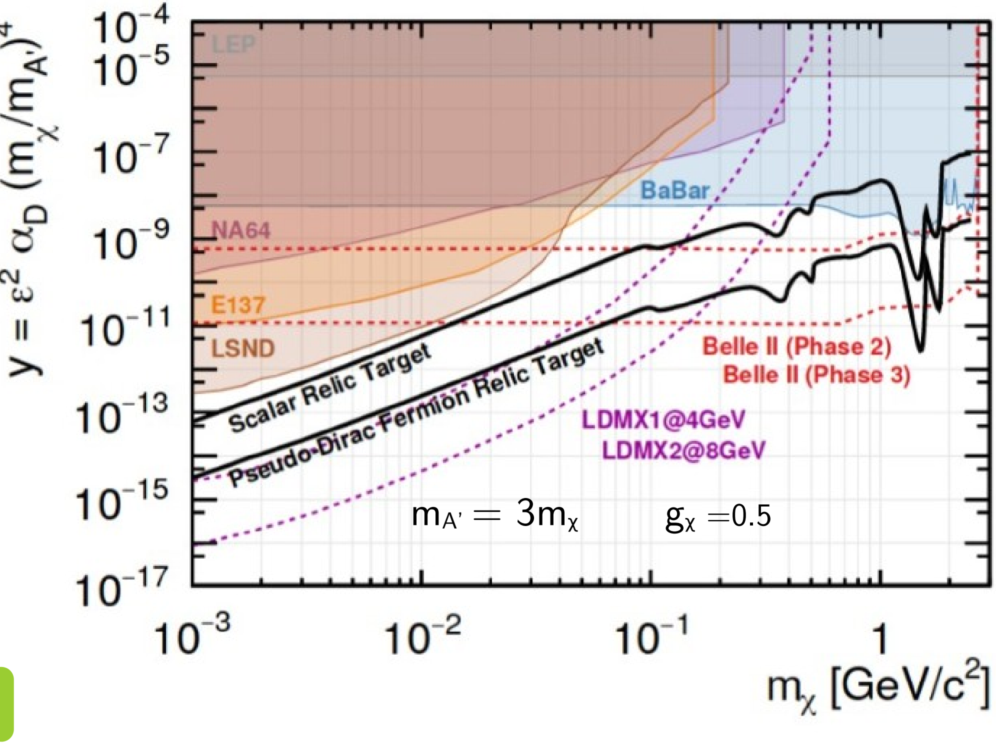
A' → ll **Visible decay** to lepton pair

A' → χχ **Invisible decay** to DM

Narrow dilepton resonances

Missing mass/momentum

Search type



The Belle II Physics Book, PTEP 2019 (2019)

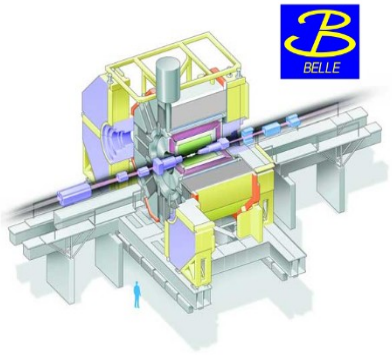
Experiments at B-factories

B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs → **CP violation studies**.

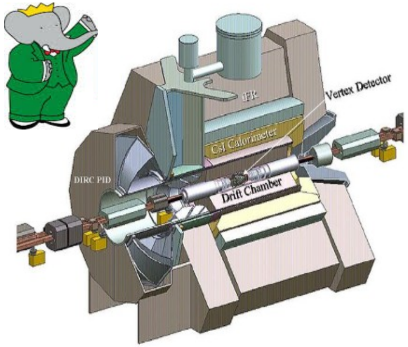
$$\boldsymbol{e^+e^- \to \sqrt{s} = 10.58\ \text{GeV}\ (\Upsilon(4S)) \to B\bar{B}}$$

$\Upsilon(nS)$ = bound state of b quark and $\bar{b}$ anti-quark. ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb)

First generation of B-factories (operation ~1999-2010)



at the KEKB collider
(KEK, Japan)



at the PEP II collider
(SLAC, California)

- **Clean environment *of lepton collider*** → lower background, high resolution
- **Hermetic detector** with excellent PID capability → efficient reconstruction of ***neutrals*** (π^0, η, …), ***recoiling system*** and ***missing energy*** final states

Dark higgsstrahlung: analysis strategy

- A' reconstructed as muon pairs, $M_{\mu\mu} > 1.65$ GeV for trigger requirements

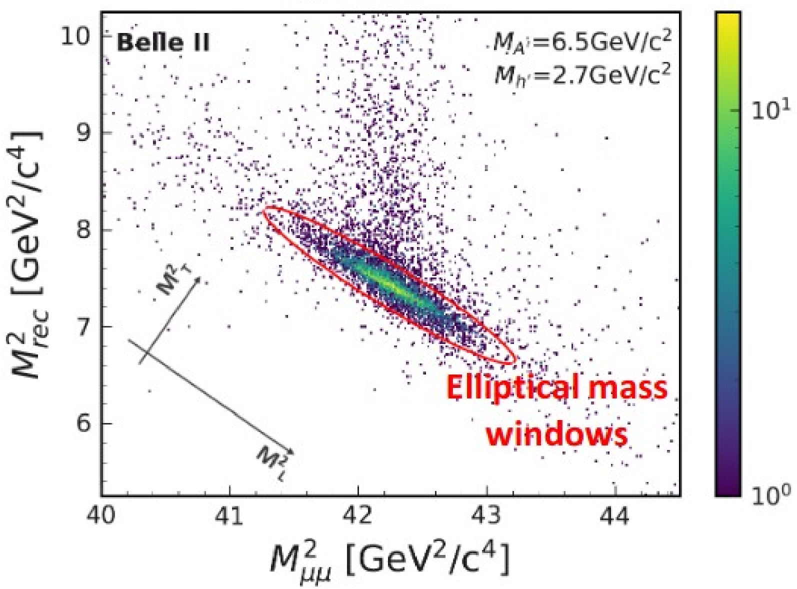
  → *Additional kinematic constraint: **resonant** dimuon candidate,* peak in direct mass

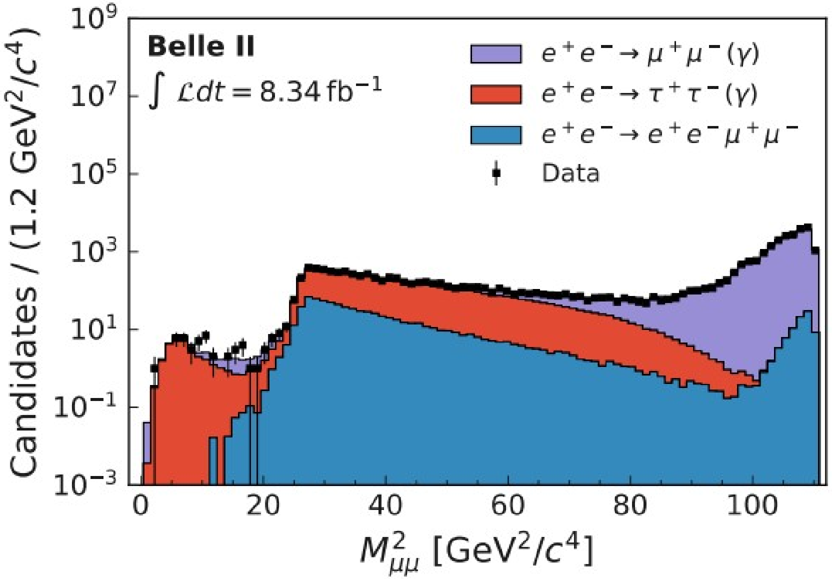
- Scan dimuon and recoil mass searching for peaks in 9000 sliding elliptical windows

- Apply Bayesian counting technique (challenging look-elsewhere effect)

→ Final recoil spectrum in good agreement between data and simulation

Signal simulation

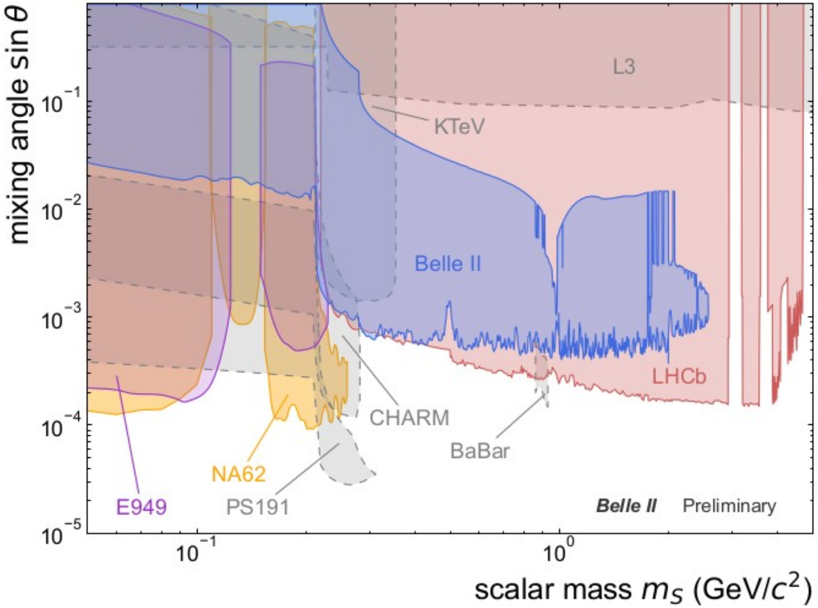


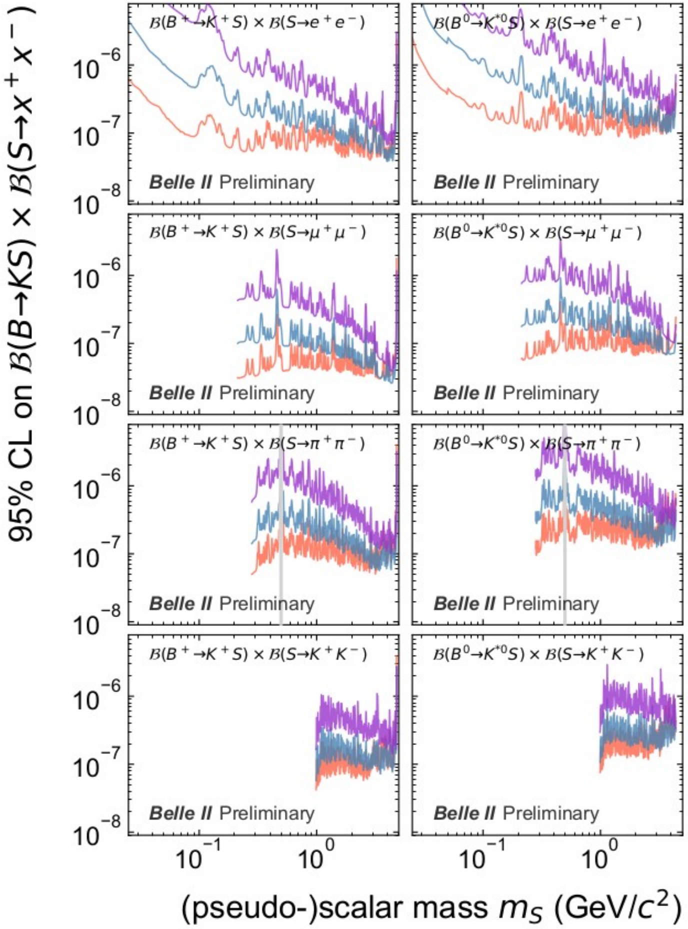


First model independent results for LLP

- No significant excess found in **189 fb^{-1}** → **first model-independent** 95% CL upper limits on BF(B→KS)×BF(S→x^+x^-)
  - → First limits on decays to hadrons
- Translate into model dependent limits on m_S vs sinθ_S, with cτ_S = f(m_S, θ_S)

Dark Higgs-like scalar S model interpretation [1]

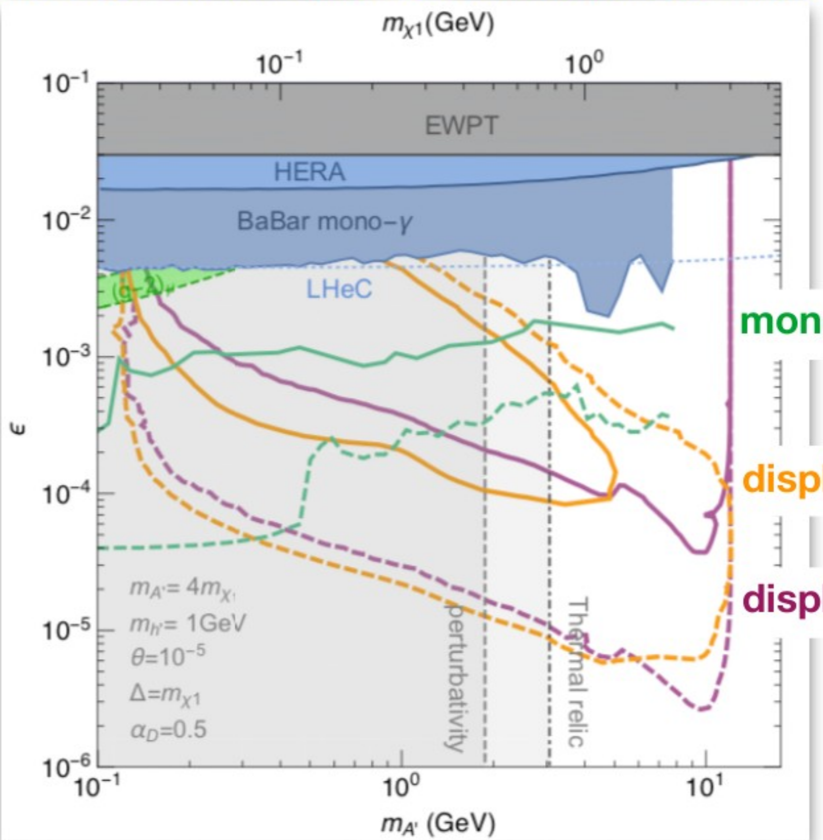




[1]: Phys. Rev. D 101 095006 (2020)

Belle II reach in IDM searches

Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg, 2012.08595



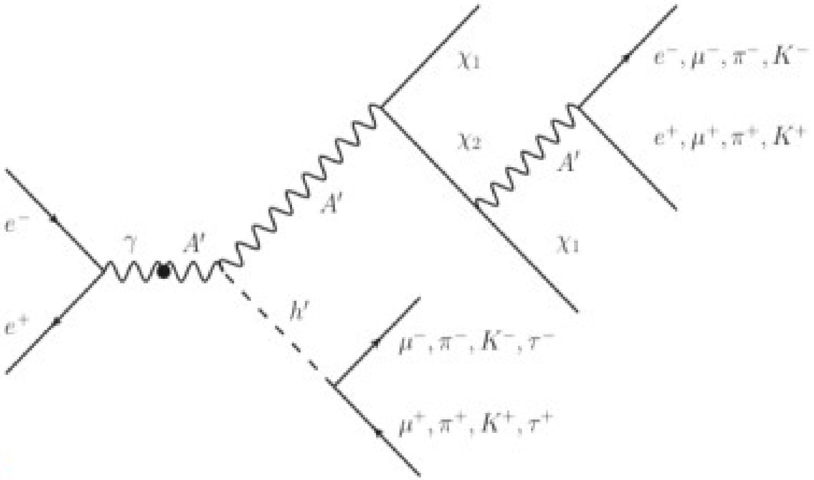
— 100/fb

······· 50/ab

mono-photon

displaced+photon

displaced (two pairs of charged particles, at least one pair displaced)



Look for dark-higgsstrahlung

+ A' decays to DM +FSR A' (→ SM SM) production

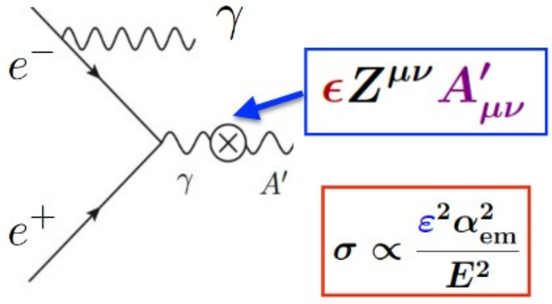
Displaced vertex trigger
is very important to obtain a good reach!

“0.9 cm < Rxy < 60cm, and a transverse momentum of the corresponding particles of pT > 100 MeV each”

Invisible signatures

Example scenario: invisible dark photon

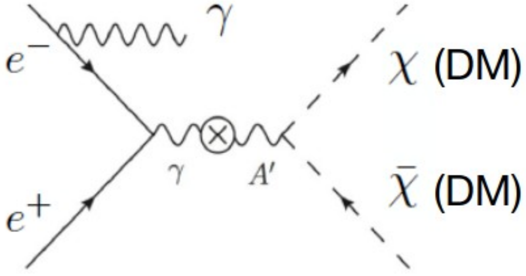
Production of a dark photon
at B-factories:



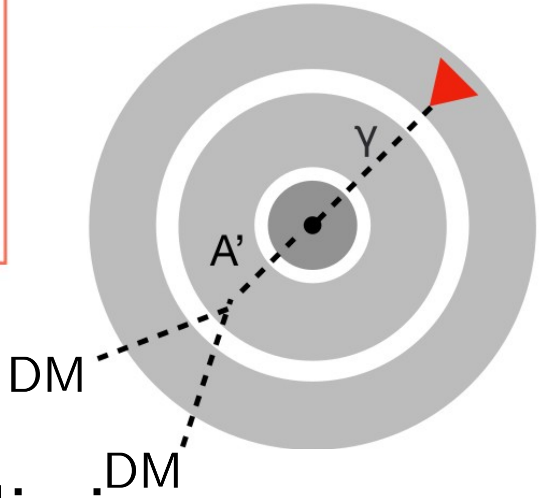
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

$\sigma \propto \frac{\varepsilon^2 \alpha_{\rm em}^2}{E^2}$

Decay of the dark photon:



photon + invisible

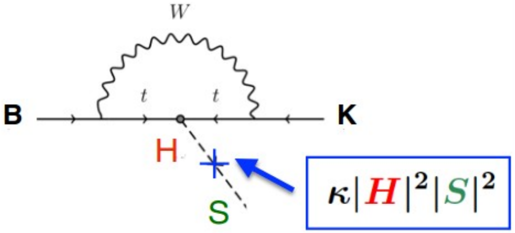


Missing energy

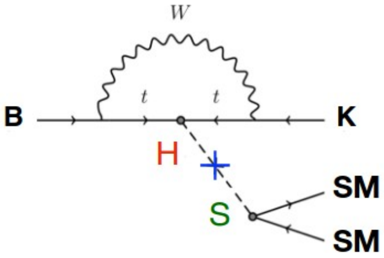
Visible signatures

Example scenario: visible dark scalar

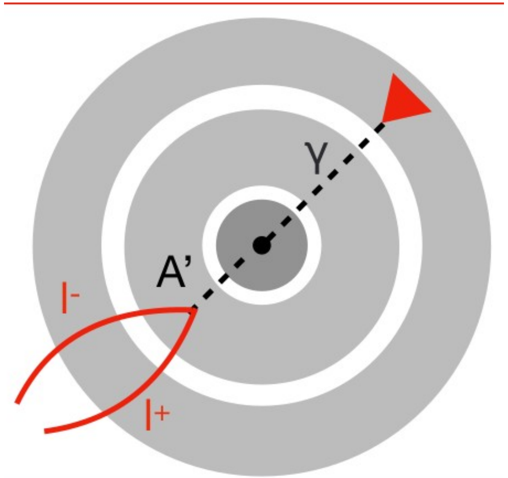
Production of a dark scalar
at B-factories:



Decay of the dark scalar:

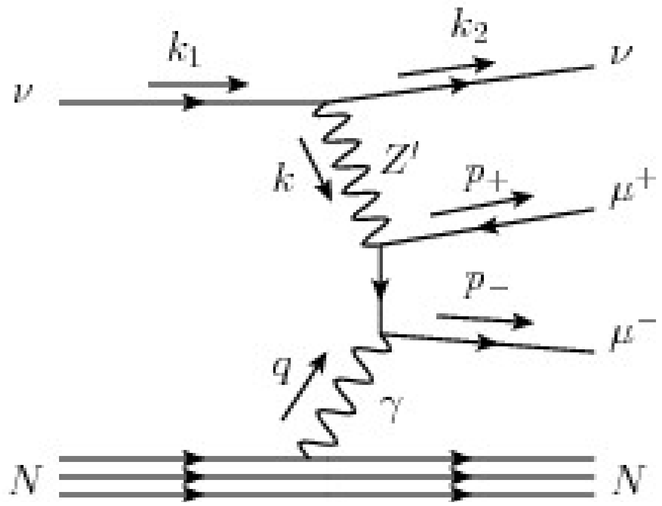


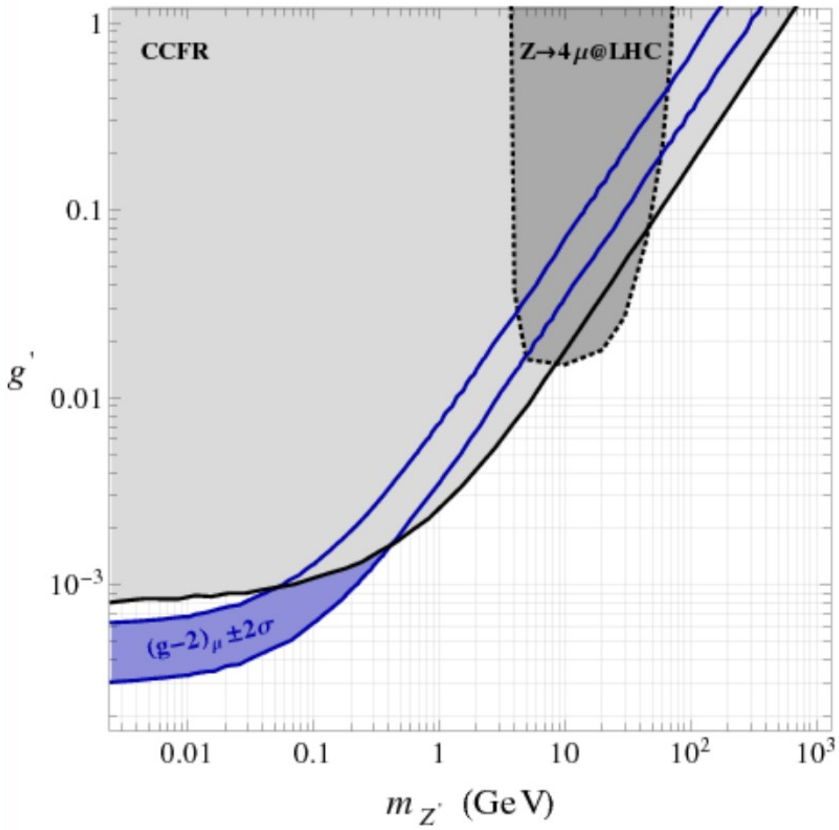
B→KS→Kμμ



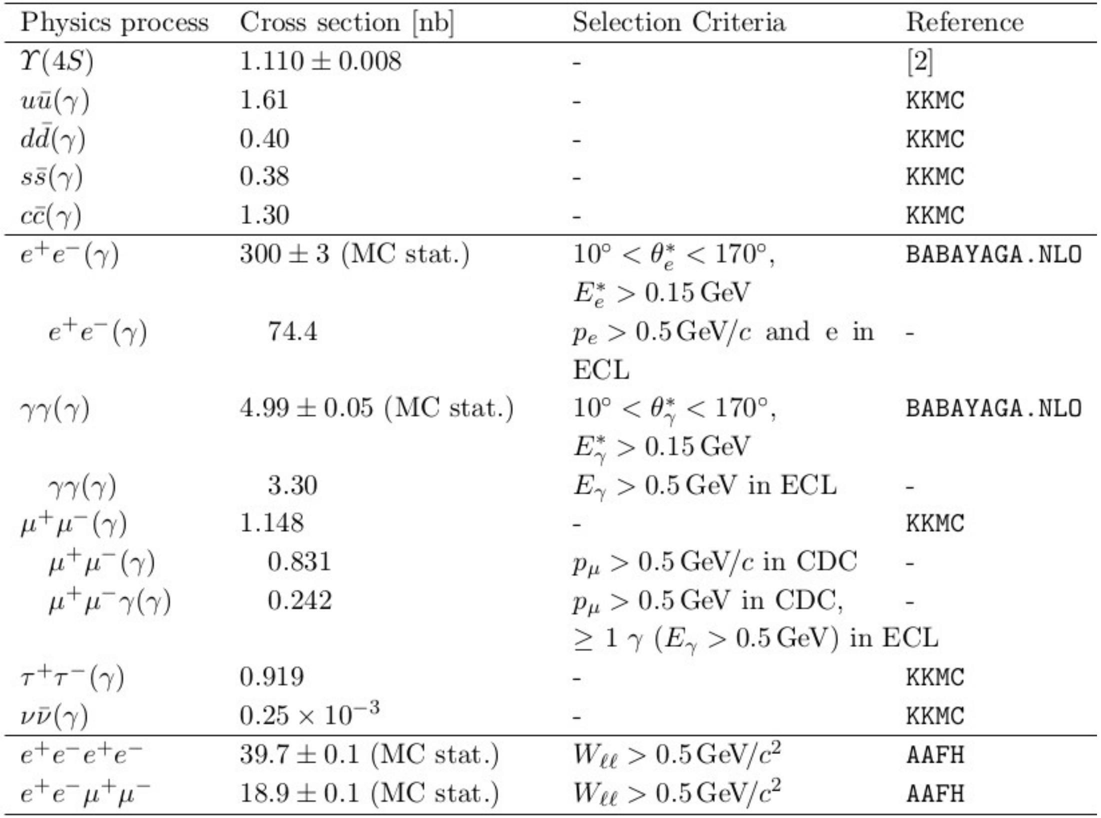
Nuclear reactions

- Neutrino trident production with a Z' boson





Cross section in e^+e^- collision at 10.58 GeV



Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	`KKMC`
$d\bar{d}(\gamma)$	0.40	-	`KKMC`
$s\bar{s}(\gamma)$	0.38	-	`KKMC`
$c\bar{c}(\gamma)$	1.30	-	`KKMC`
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\mathrm{GeV}$	`BABAYAGA.NLO`
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	`BABAYAGA.NLO`
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	`KKMC`
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma$ ($E_\gamma > 0.5\,\mathrm{GeV}$) in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	`KKMC`
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	`KKMC`
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	`AAFH`
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	`AAFH`

The Belle II Physics Book [arXiv:1808.10567]

- Low multiplicity event cross sections rapidly diverge compared to hadronic ones
- Selections applied at MC generator level to reduce the effective cross section (acceptance, particle momentum selections)
- W_{ll} is the minimum invariant secondary fermion pair mass

Example:
Z' → invisible (2018)

Upper limit computation

- **Signal yields** extracted by applying a **Poisson counting experiment** technique, in each recoil mass bin, after the final selections → **Upper limits** on the cross-section $\sigma_{Z'}$ are computed in a Bayesian approach

Upper limit computation in the Bayesian approach

(BAT software framework: https://doi.org/10.1016/j.cpc.2009.06.026)

- N_{obs}, B_{exp}: Poissonian likelihood
- Prior distribution for Z' cross section: positive, flatly distributed in 0-10^5 fb
- Systematic uncertainties: modeled with Gaussian functions with width equal to the size of the estimated effect
  → integrate over nuisance parameter priors (*marginalization*)
  → integrate the likelihood until the value of the integral reaches the wanted credibility level (0.90)