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Roma Tre – Seminar cycle for PhD

DARK SECTORS AND WHERE TO FIND THEM

Today's **Highlights**

- Why dark matter?

DISCLAIMER: I am not a theorist...

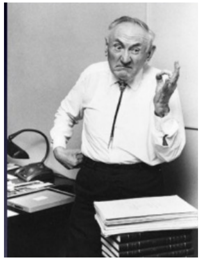
- Why dark sectors?
- How to search for dark sectors?
  - Focus on searches at B-factories
  - Beyond minimal dark sector searches

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:

$2E_{kine} = - U$

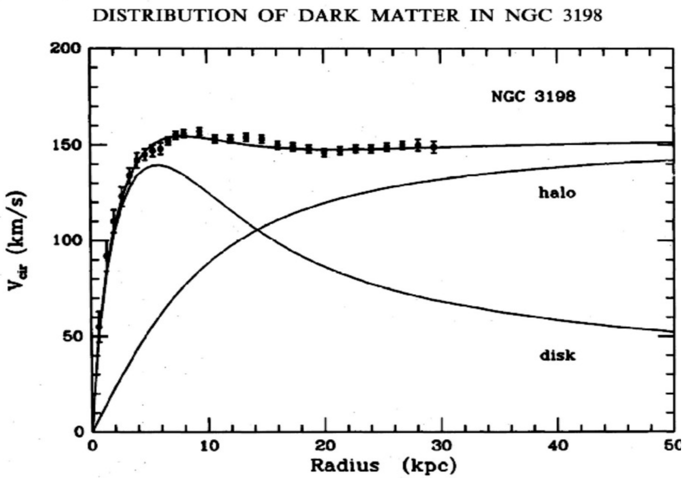
$\boldsymbol{<v(r)^2> = GM(r)/r}$

M(r) ~400x luminous matter

V.Rubin, 1970s

Flat rotational curves:

$v(r) = const$



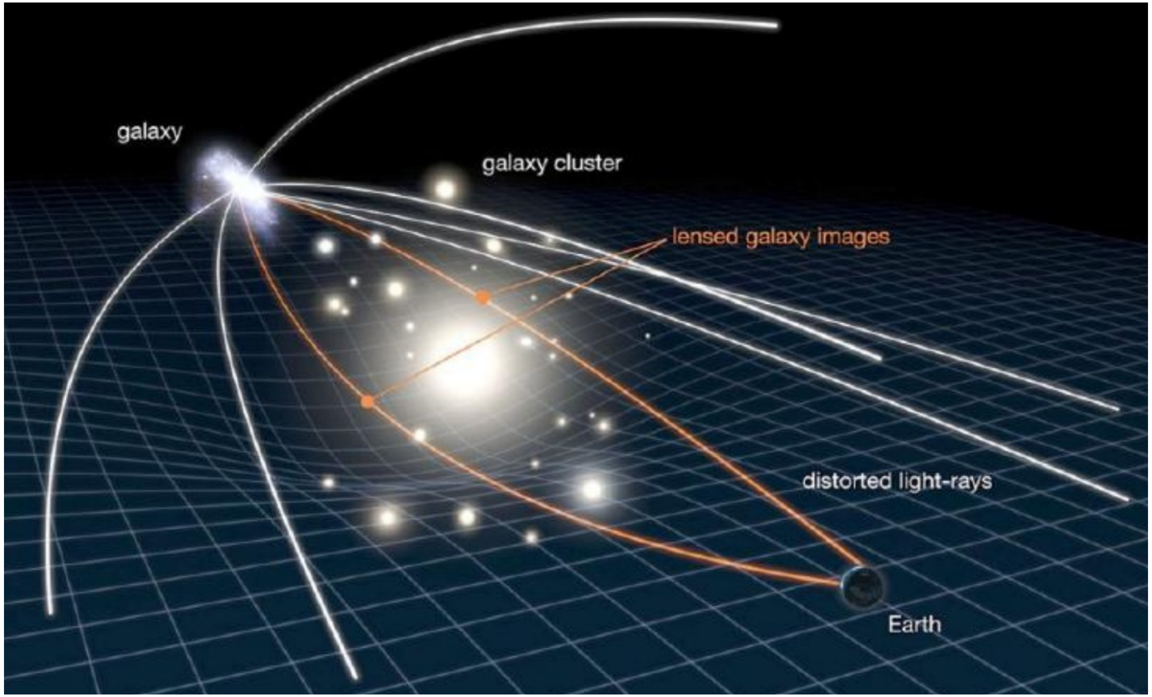
→ mass distribution linearly growing with r (assuming $\rho(r)=1/r^2$)

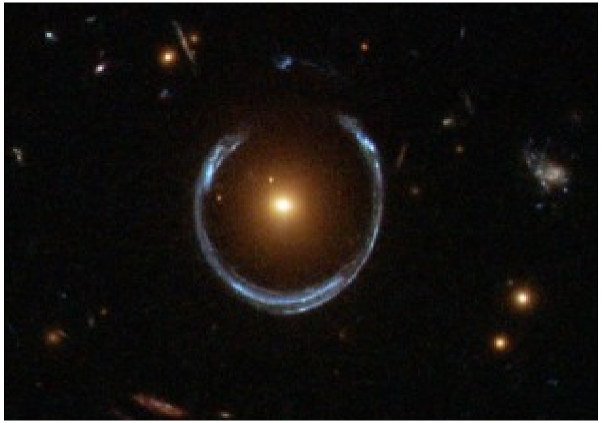
→ DM gravitates

Evidences for dark matter (II)

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

Gravitational Lensing



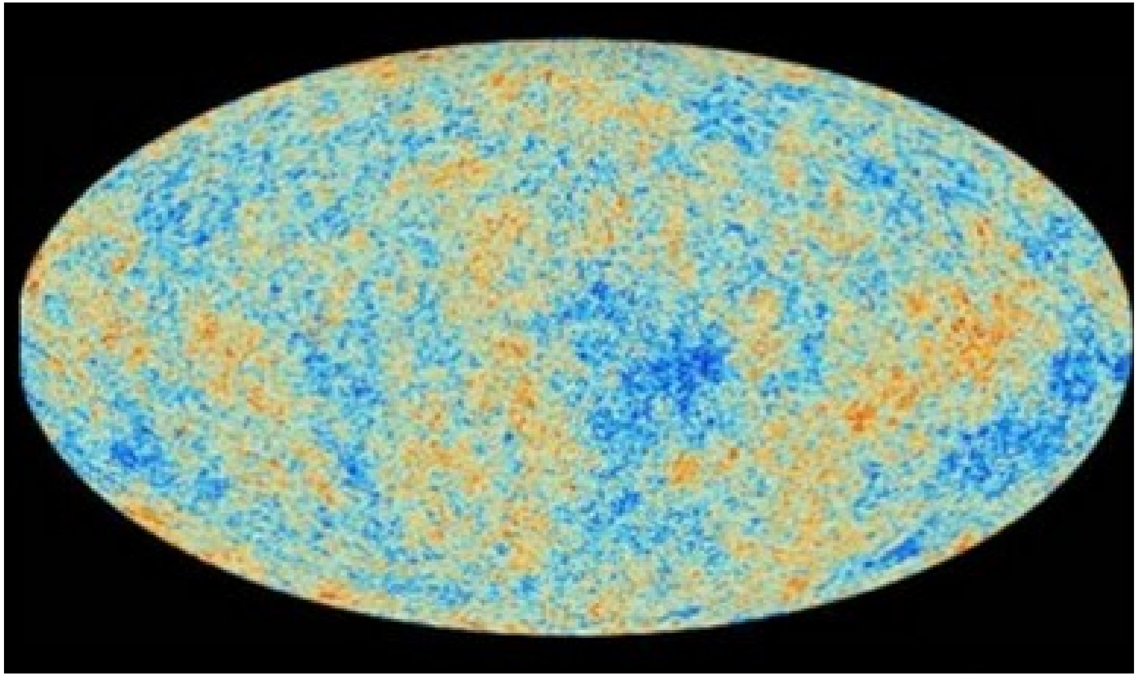


→ it's dark (doesn't interact electromagnetically)

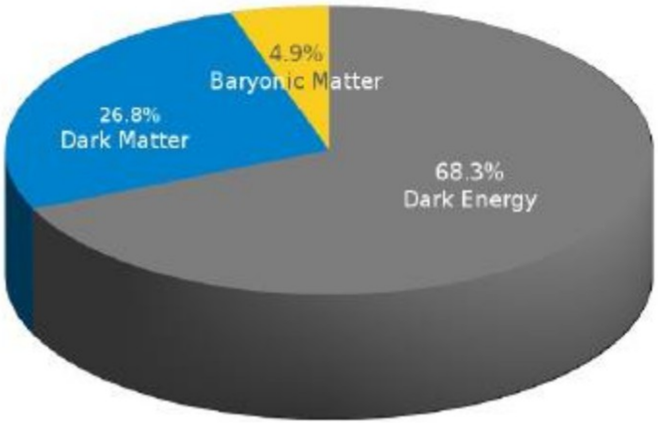
Evidences for dark matter (III)

- 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

$\rightarrow$ 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*

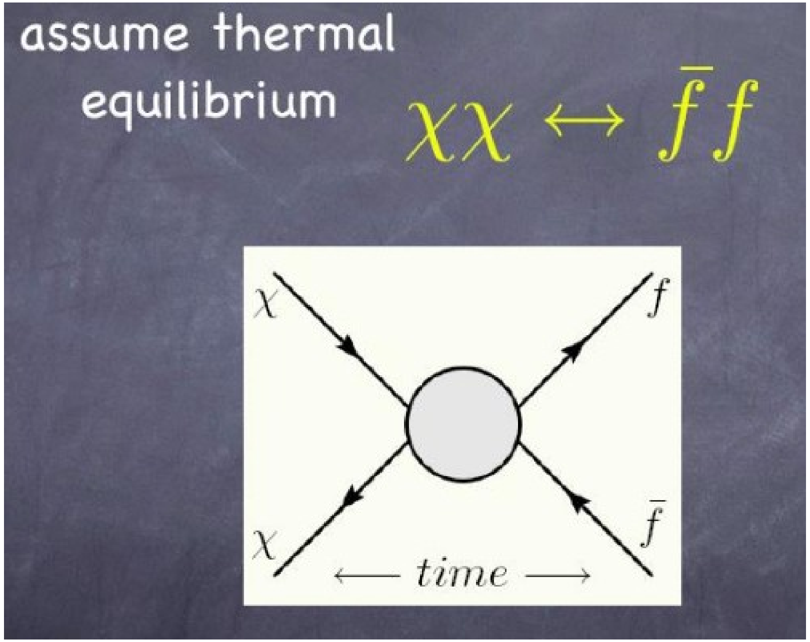
experimental input from cosmological observation.

- **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)

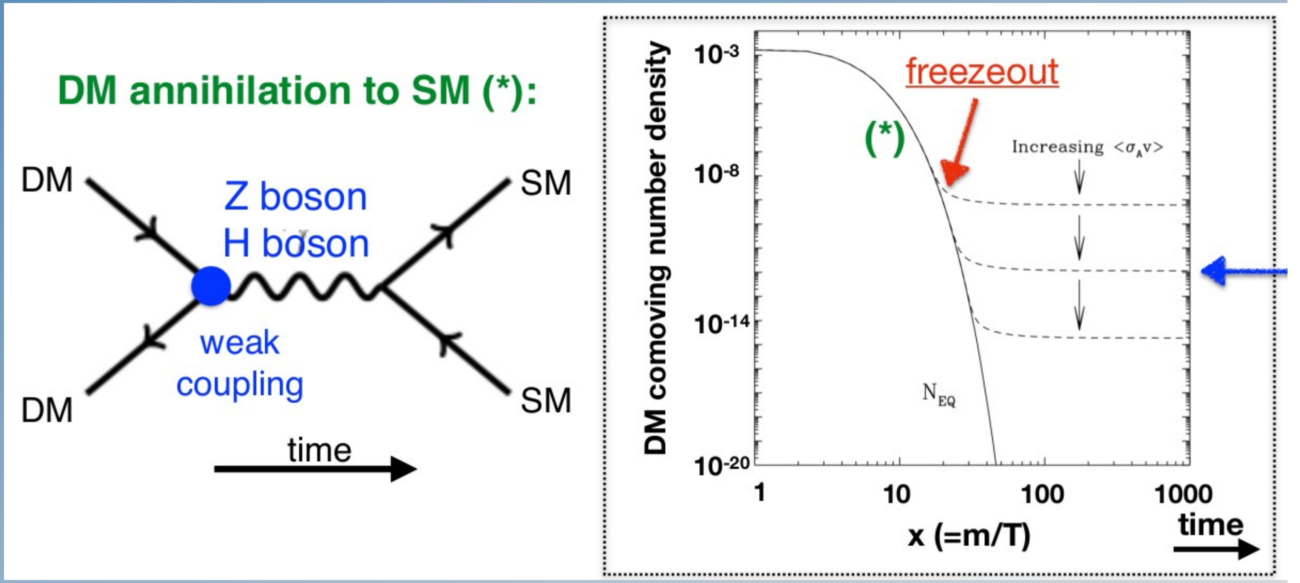
$$n_{\mathrm{DM}}^{(\mathrm{eq.})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$



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^3s^{-1}

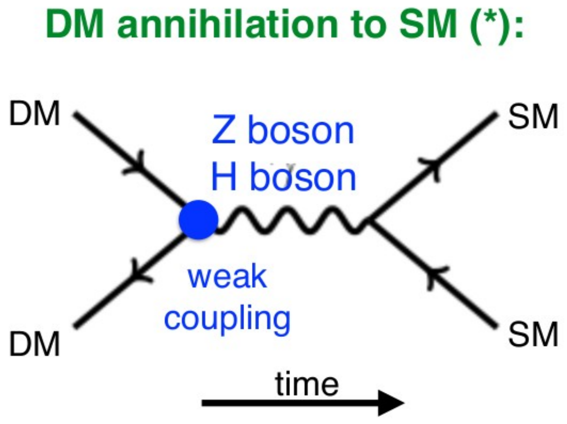
Thermal relic density: *freeze out* mechanism

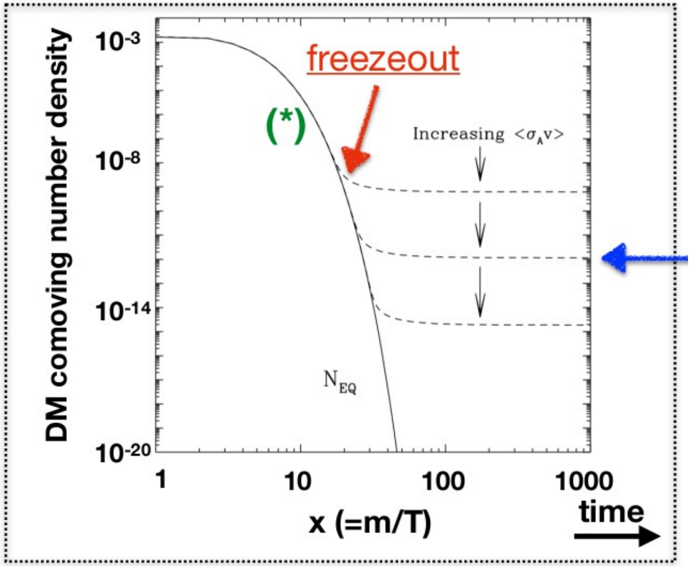


The WIMP "miracle"

- 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



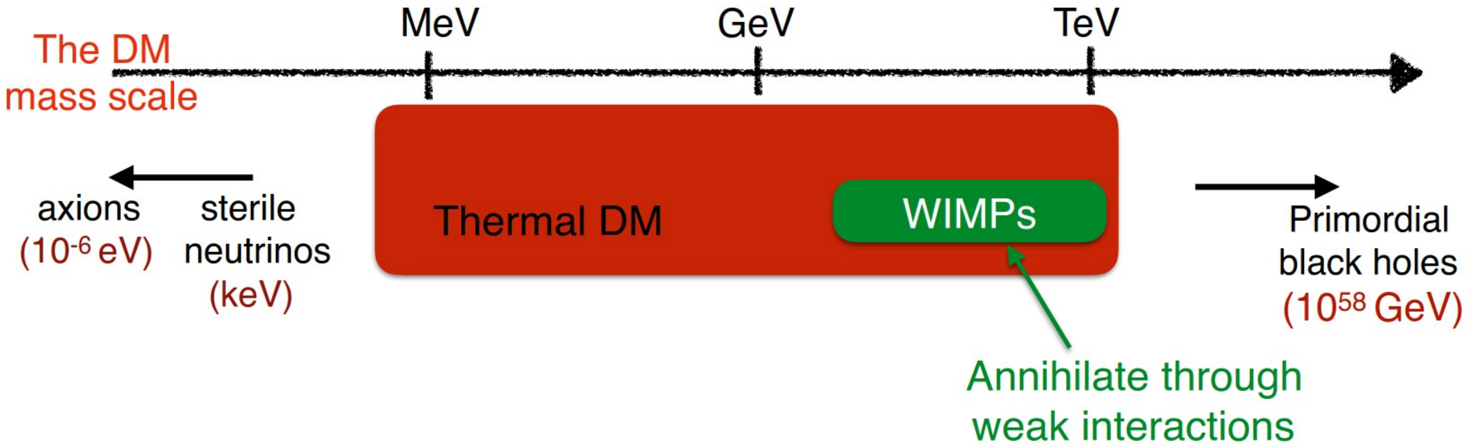


BUT…more recent constraints exclude vanilla WIMP models

Dark matter mass scale

- We do not know the DM mass scale

$\rightarrow$ different searching strategies and techniques



Dark matter and dark sectors

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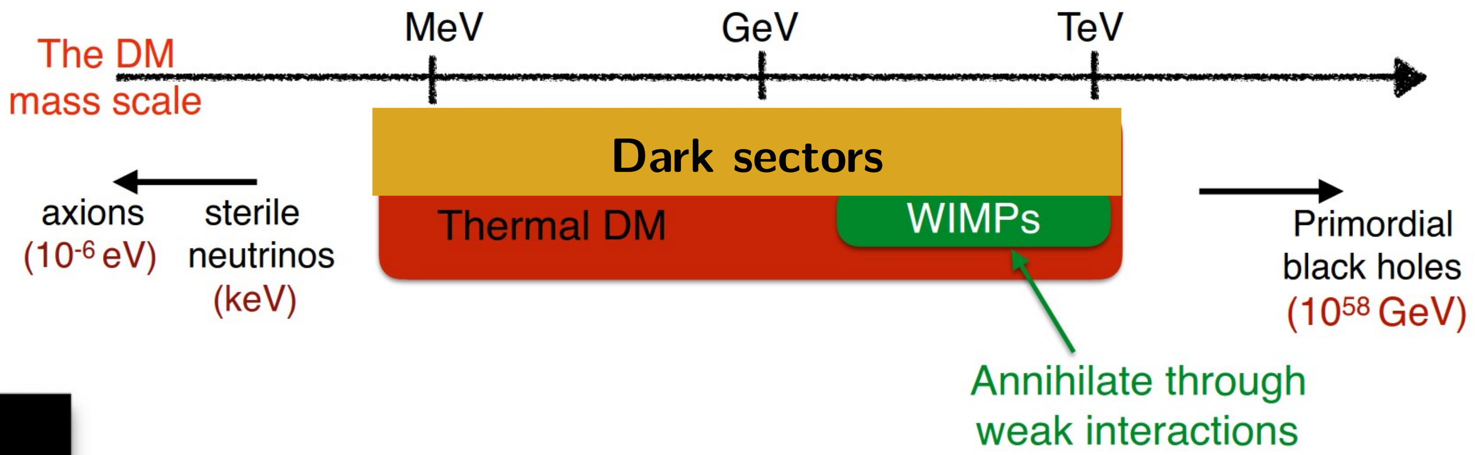
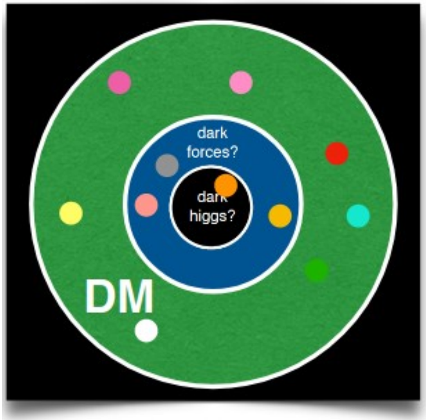
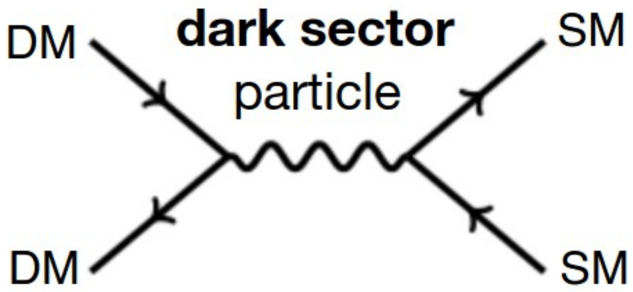




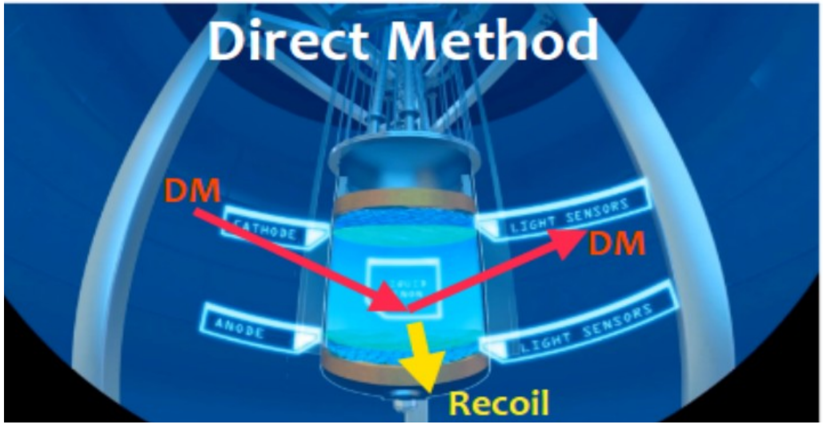


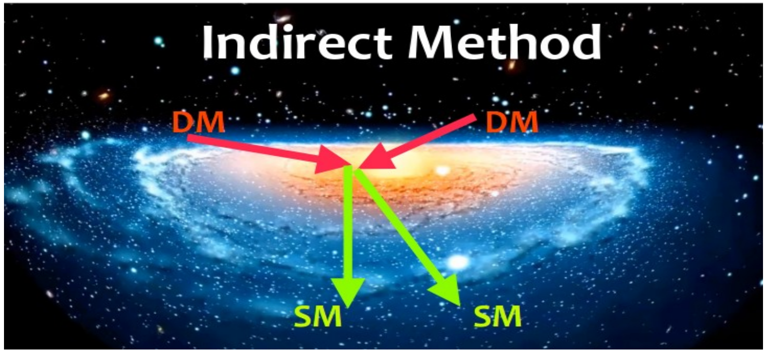
Hidden (**neutral** under SM interactions) sector that communicates with SM through a **portal** (new mediator)

Dark matter detection

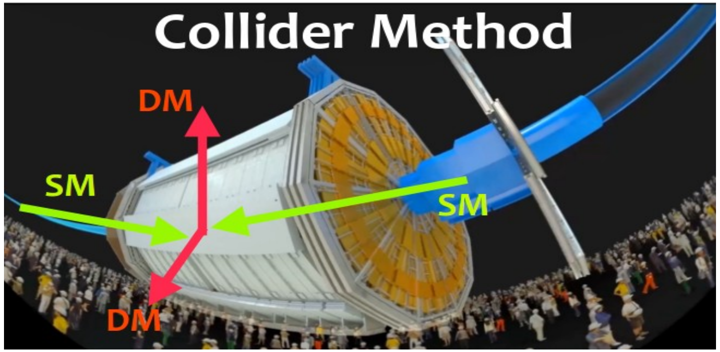
How to search for it?

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





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

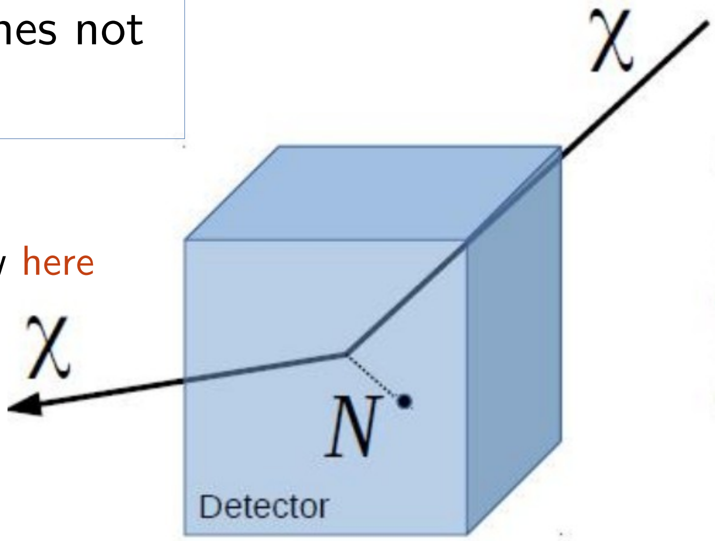


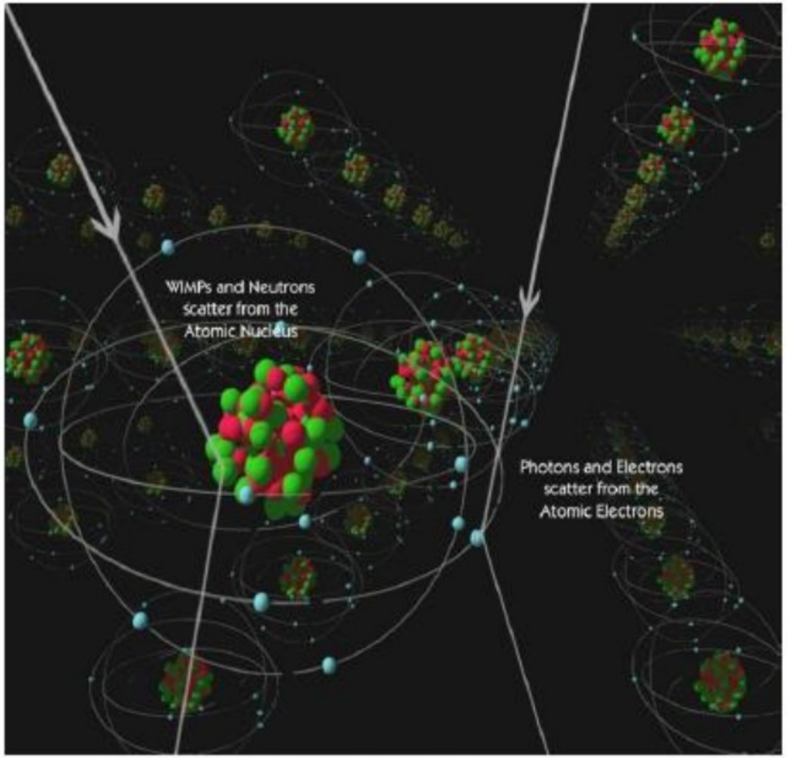
3) If DM weakly couples to SM it can be produced in *SM particles annihilation* at ***accelerators (colliders, fixed-target experiment)***

Principles of direct detection

Disclaimer: direct searches not treated in this seminar

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





Type of detectors:

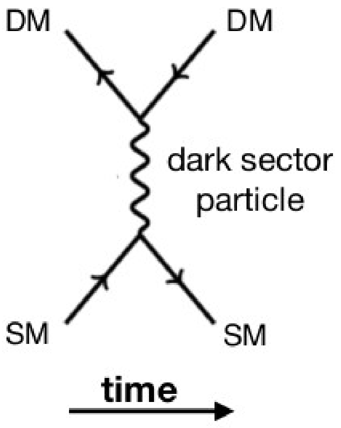
- Liquid gas (2-phase)
- Cryogenic detectors
- Scintillation
- Bubble chambers...

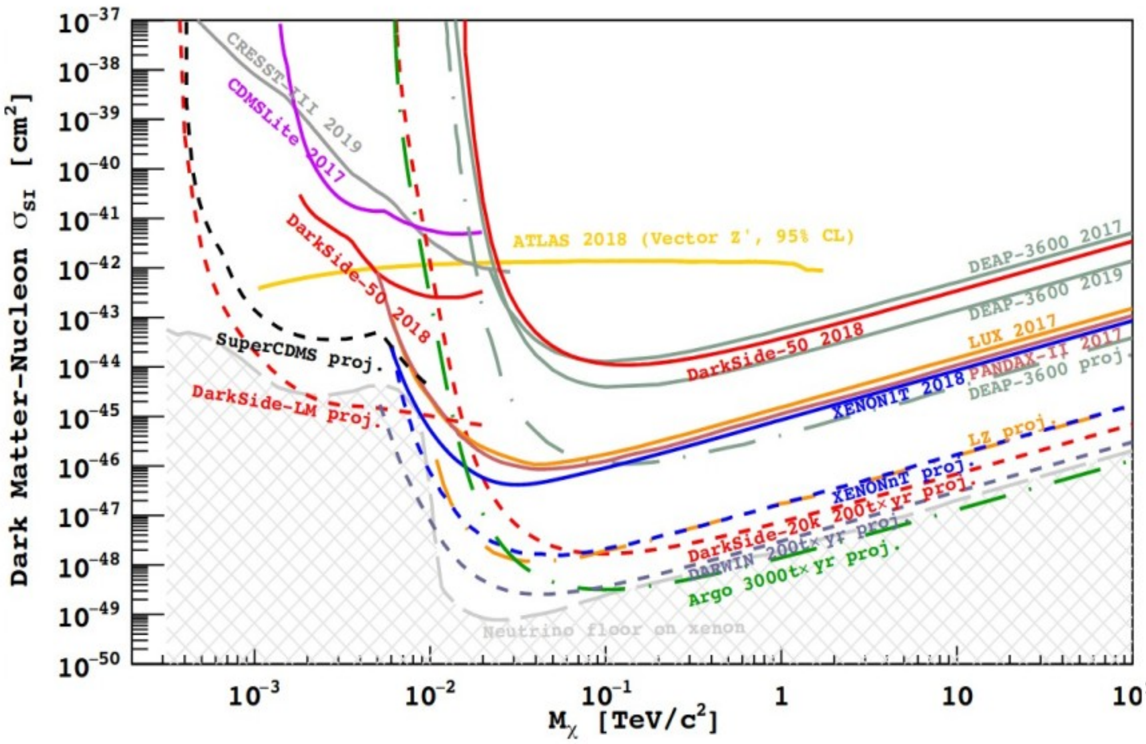
Type of interactions:

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

Direct detection (weak) bounds

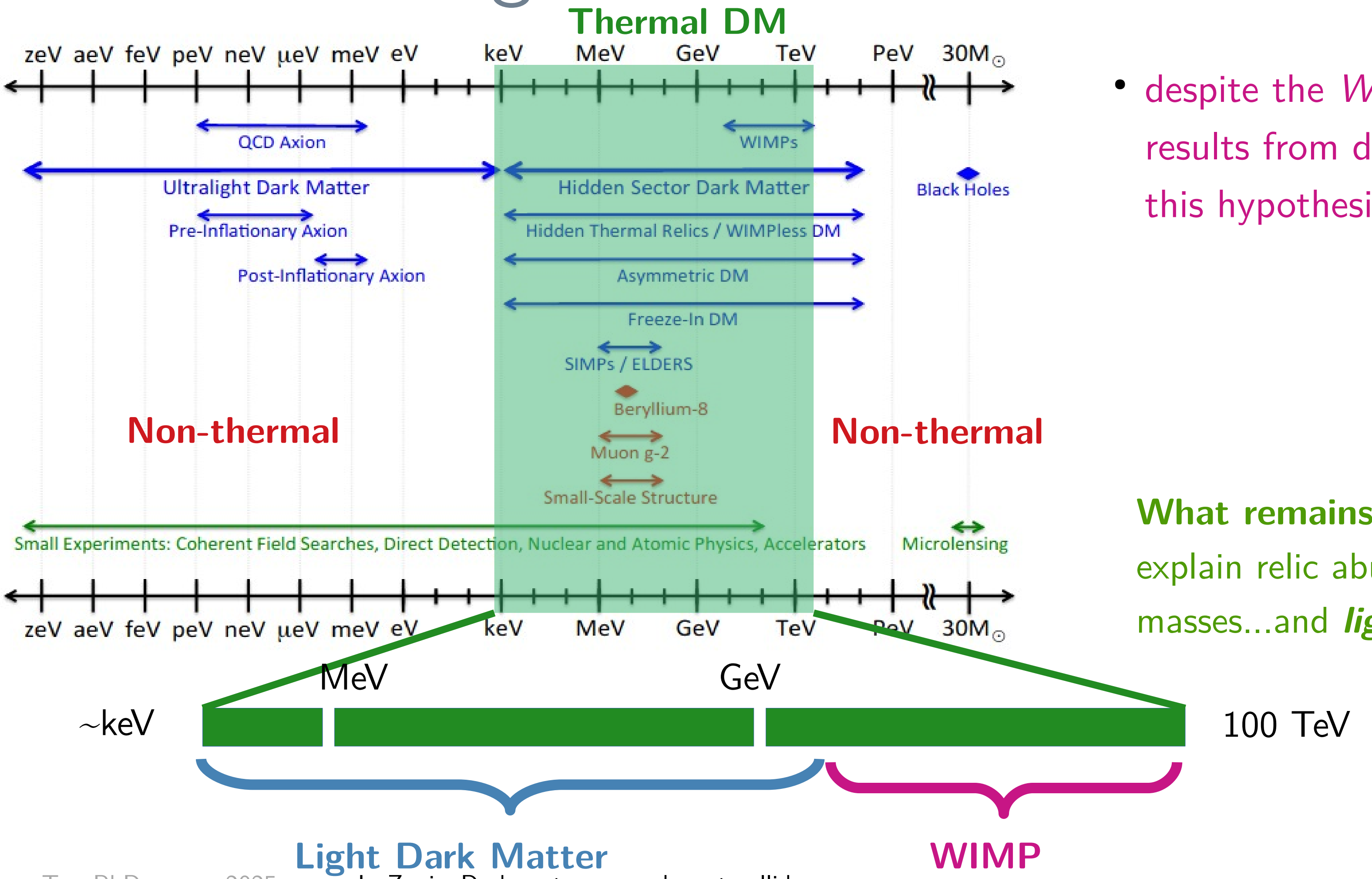
- Lower energy thresholds for the scattering recoil allow to access masses **above GeV scale**





- 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. $(g\text{-}2)_{\mu}$, rare B meson decays)

$\rightarrow$ **signatures similar to dark matter searches**

Muon anomalous magnetic moment

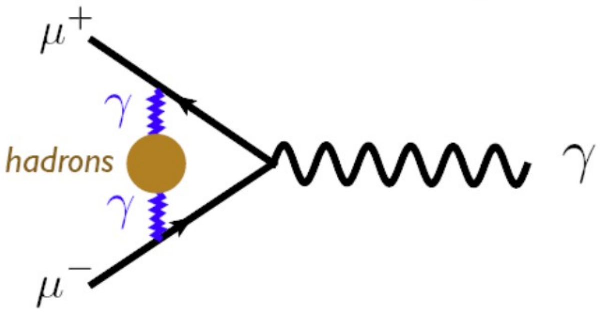
magnetic dipole moment of charged particle

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

spin

can be measured very accurately

e.g.



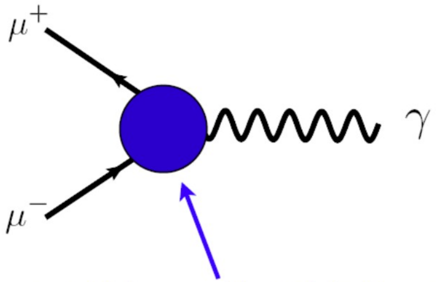
$g_s \neq 2$

(Standard Model)

difficult to calculate precisely in Standard Model...

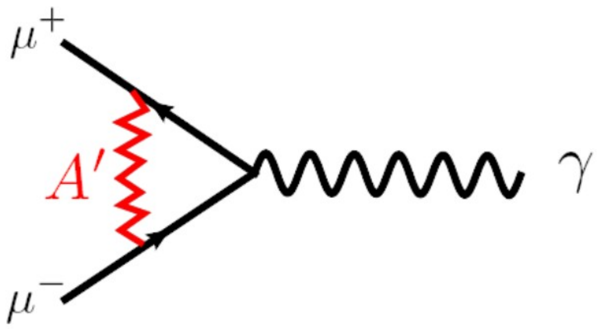
Standard Model $(g_s - 2)_\mu$ versus Data $\sim$ 3.6 σ deviation

Evidence for New Physics?



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

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:

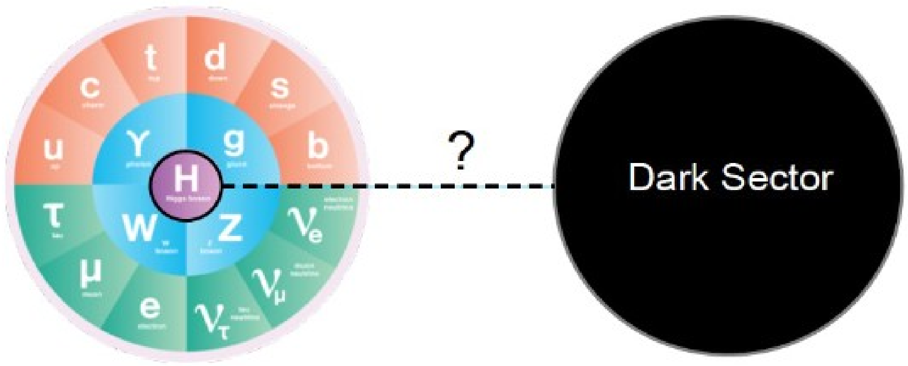
$$(g_s - 2)_\mu^{A'} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \qquad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

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

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

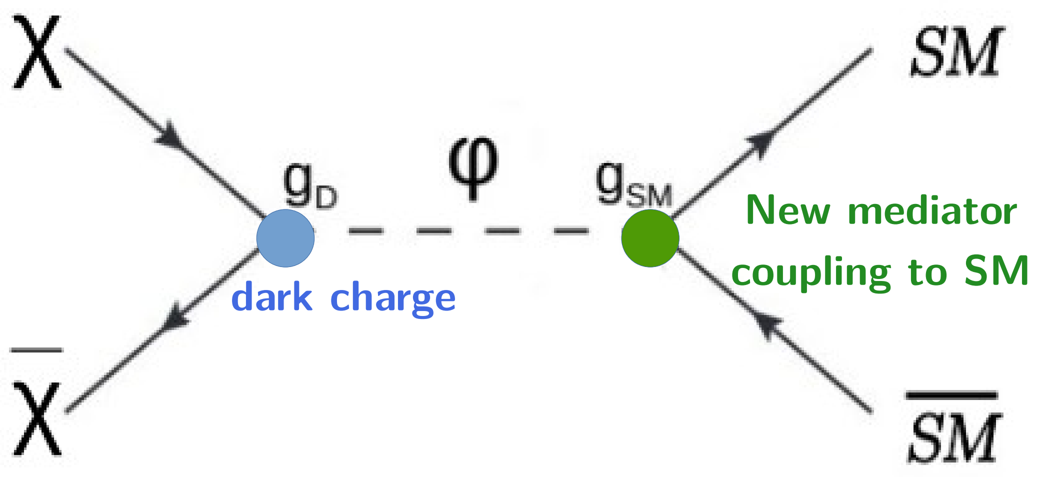


Light dark sector portals

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

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

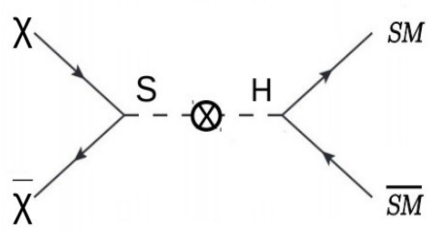
$$m_\phi^4 \leq \frac{m_\chi^2}{< \sigma v >} \text{ since g} < O(1)$$



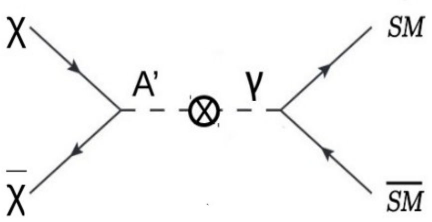
Light dark matter scenario requires the existence of new *light* mediators

Light dark sectors

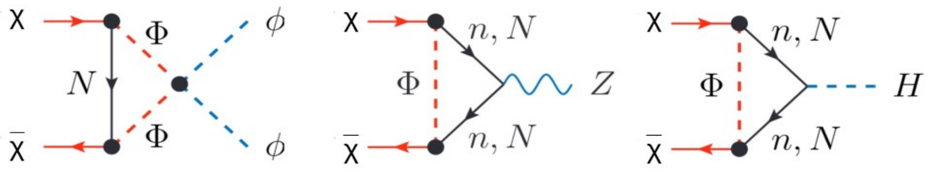
- Within allowed SM symmetries, 3 possible renormalizable portals with dimensionless couplings



1) Scalar

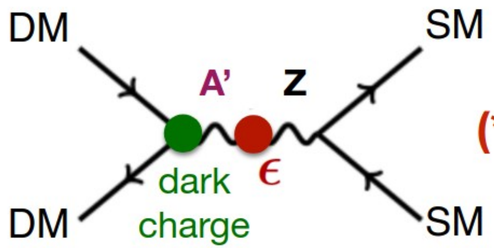


2) Vector(*)

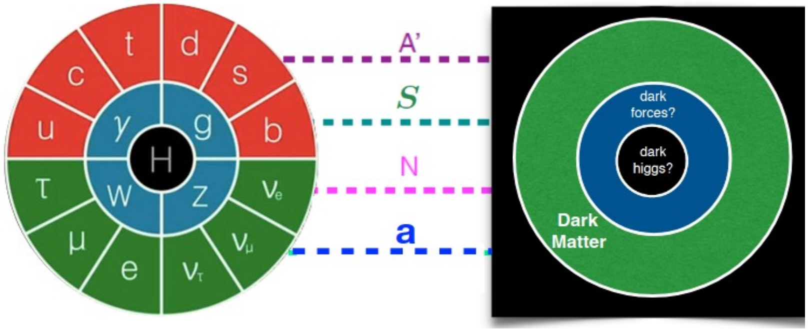


3) Neutrino portal

Example:



(*)

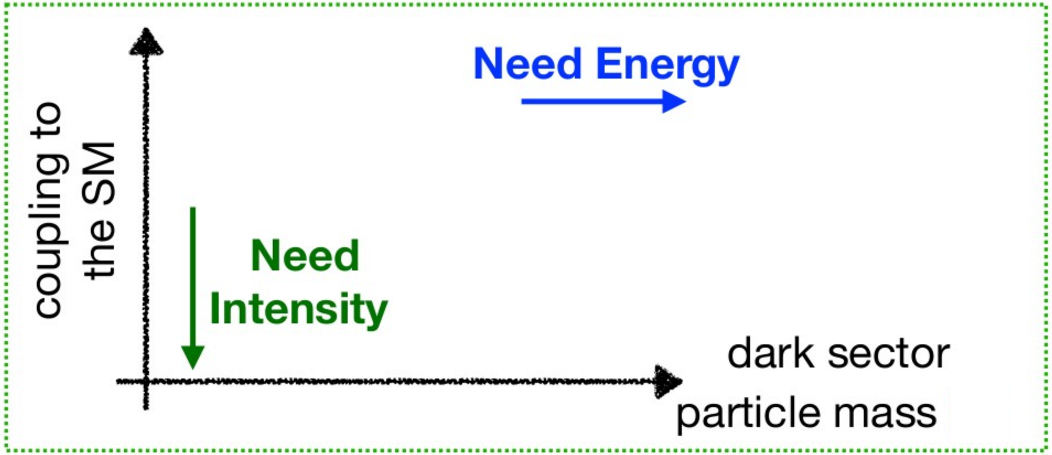


+ a not-renormalizable pseudo-scalar portal assuming Axion-Like Particles (ALPs) as mediators:

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	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$



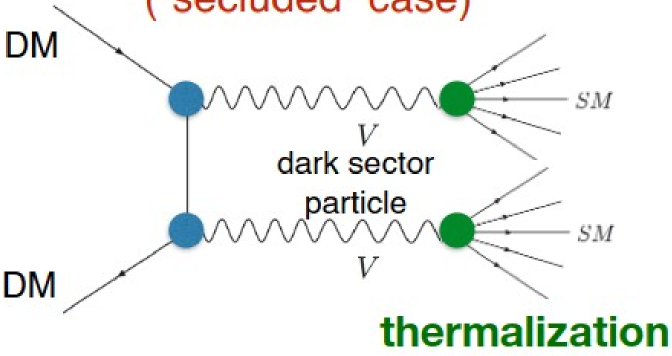
$\rightarrow$ SM weakly coupled to dark sector, possible searches at collider

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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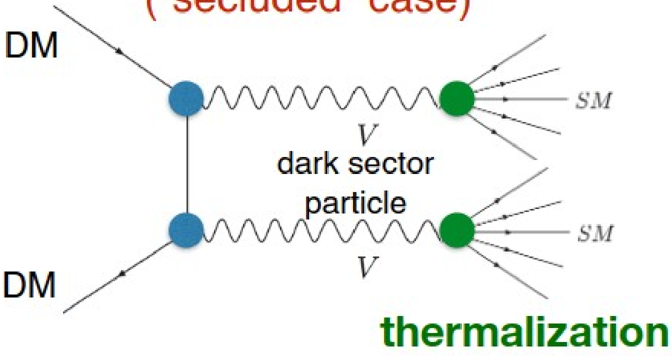

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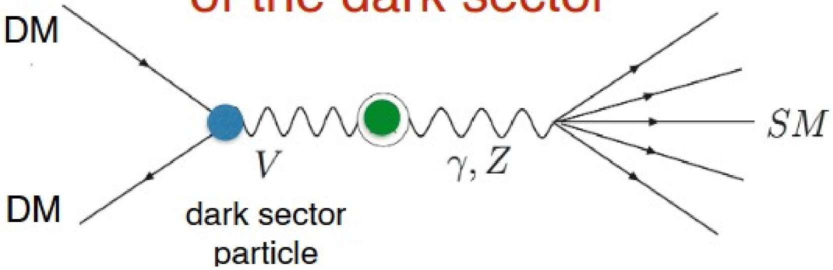
DM is the lightest state of the dark sector



→ **DM kinematically accessible**

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

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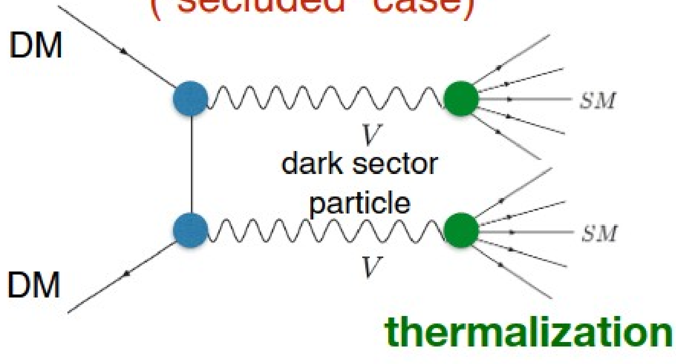

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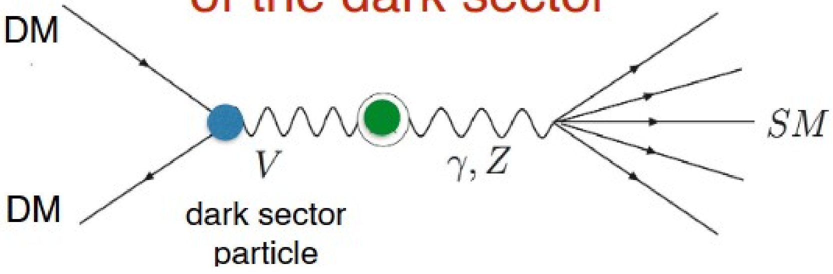

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Experimental signatures at accelerators:

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

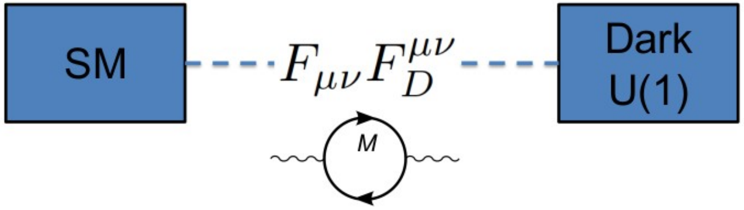
- Dark sectors are more generic than light DM and *a priori* unconstrained in their structure
- Usually they contain at least a new U(1) gauge group with an associated spin-1 massive boson A'→ the ***dark photon***
- Interaction with the SM particles are mediated by the *kinetic mixing* with the SM photon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

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

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

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 and particle physics measurements 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, $\mathbf{m_{A'} < 2m_x} \rightarrow$ 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$\rightarrow$ SM SM highly suppressed (ε^2)
  - V$\rightarrow$ DM DM is allowed, possible to look for **invisible decays** of dark photon

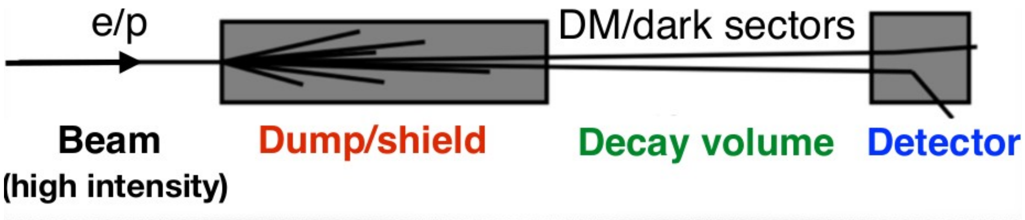
Search methods and experimental facilities

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)

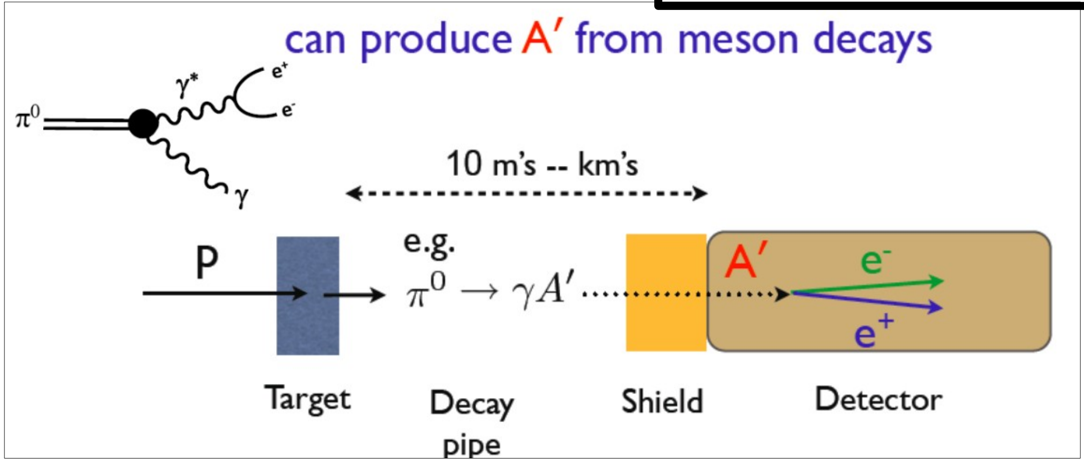
$\rightarrow$ Only some fixed target experiments were designed explicitly for the dark photon search...

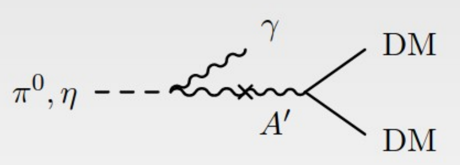
Dark photons at fixed-target experiment



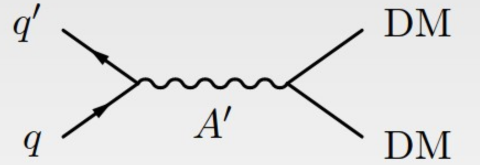
VISIBLE decays

- **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



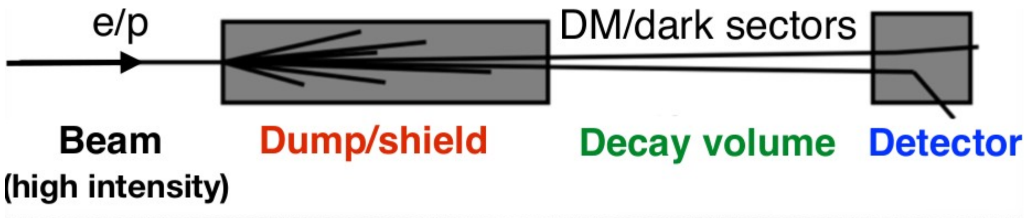


Via meson production



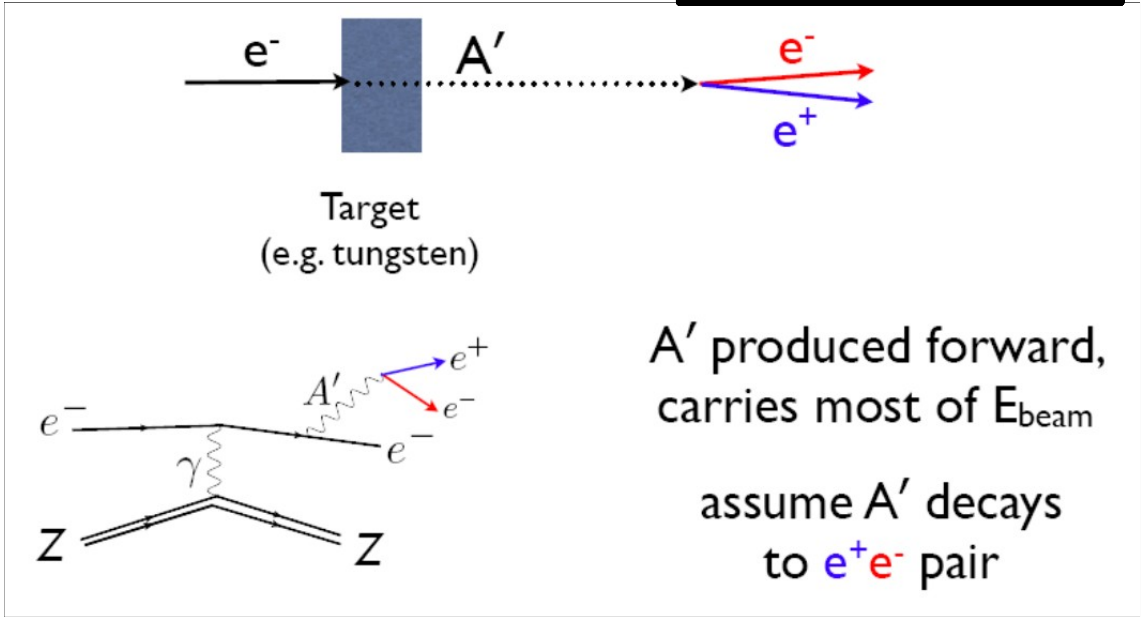
Direct production

Dark photons at fixed-target experiment

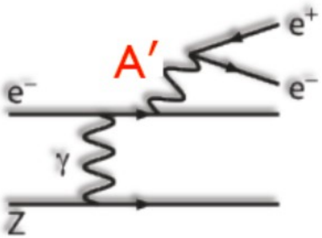


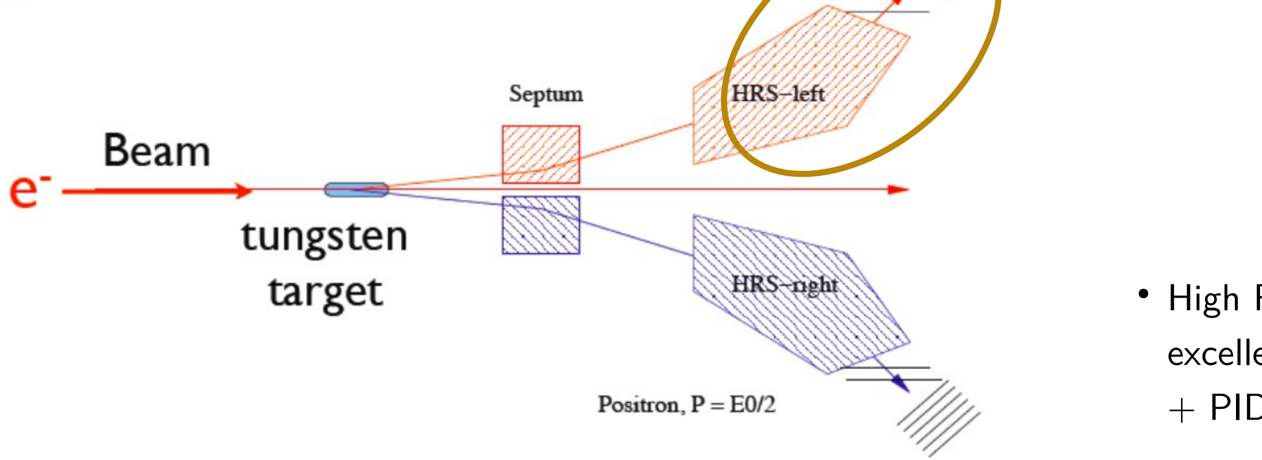
VISIBLE decays

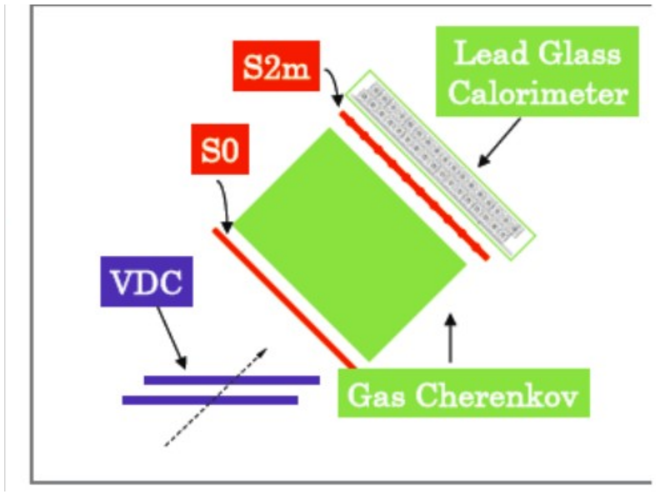
- **Electron** beam-dump
  - Larger luminosity + compact special-purpose detectors
    - scattering cross section enhanced by nuclear charge coherence
  - Suitable to investigate ***vector* portals** for mediator masses $2m_e < m_{A'} < \mathrm{GeV}$



Experimental setup







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

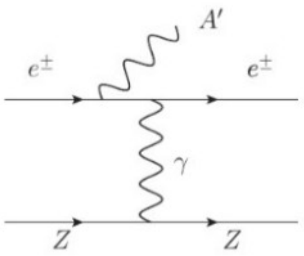
  $\rightarrow$ search for a peak in the reconstructed spectrum of e^+e^- invariant mass ($m_{A'}$)

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

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

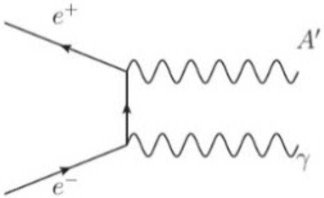
Positron enriched environment

a) A'-strahlung production



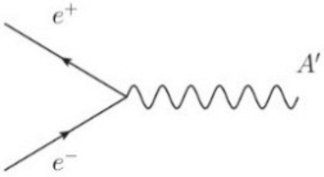
$\sigma \sim \varepsilon^2\alpha^3$

b)



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

c)

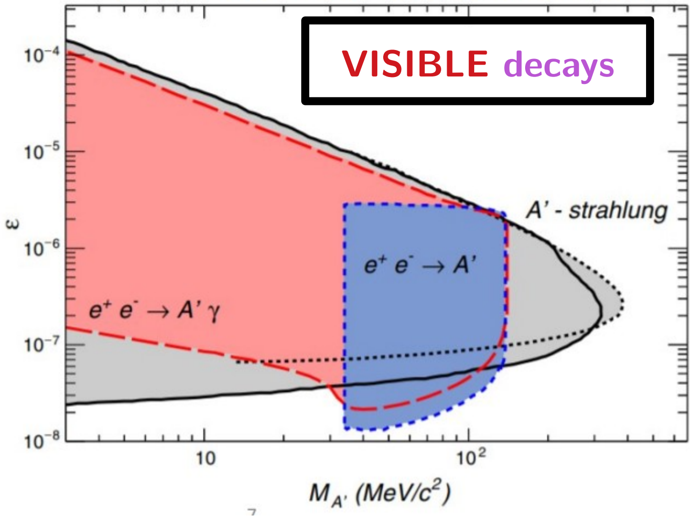


$\sigma \sim \varepsilon^2\alpha$

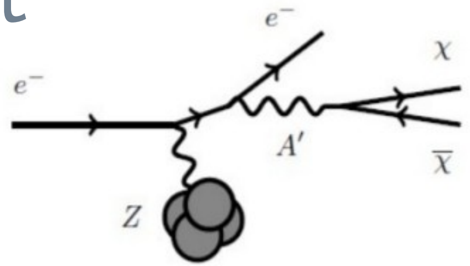
- Secondary positrons in EM showering contribute to the total A' yield with the non-resonant (b) and resonant (c) annihilation processes

  $\rightarrow$ **resonant annihilation** is enhanced! May exploit *positron beams* (**PADME** experiment at Frascati, docu)

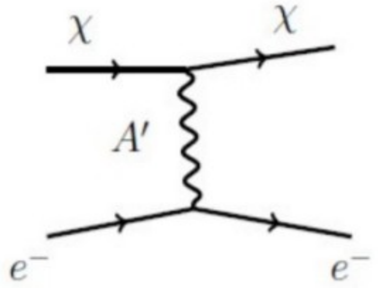
L.Marsicano *et al.* Phys. Rev. D 98, 015031 (2018)

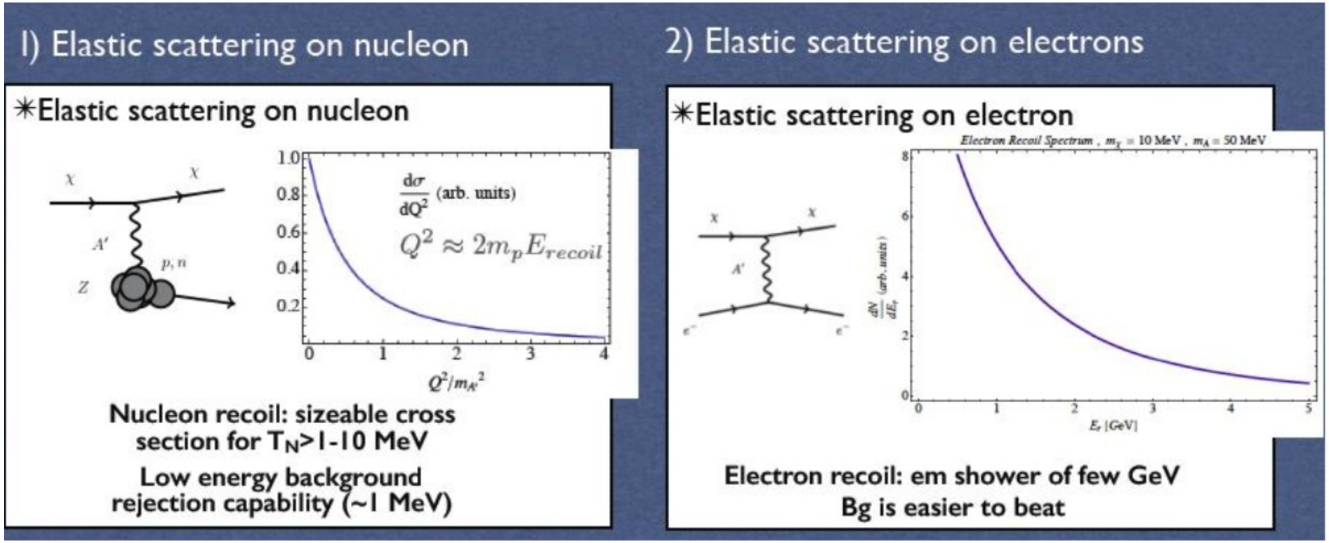


Light DM at fixed target



- Possible to **detect light DM χ** at e⁻ beam dump experiment:
  - dark photons produced radiatively through A'-strahlung and secondary positron annihilation, A' → **χχ**
  - Detect elastic scattering on electron/nucleon





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

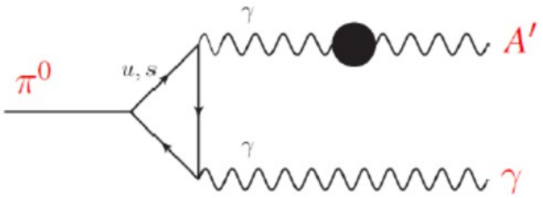
χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

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 $\pi^0 \rightarrow \gamma A'$ processes from kaon beams

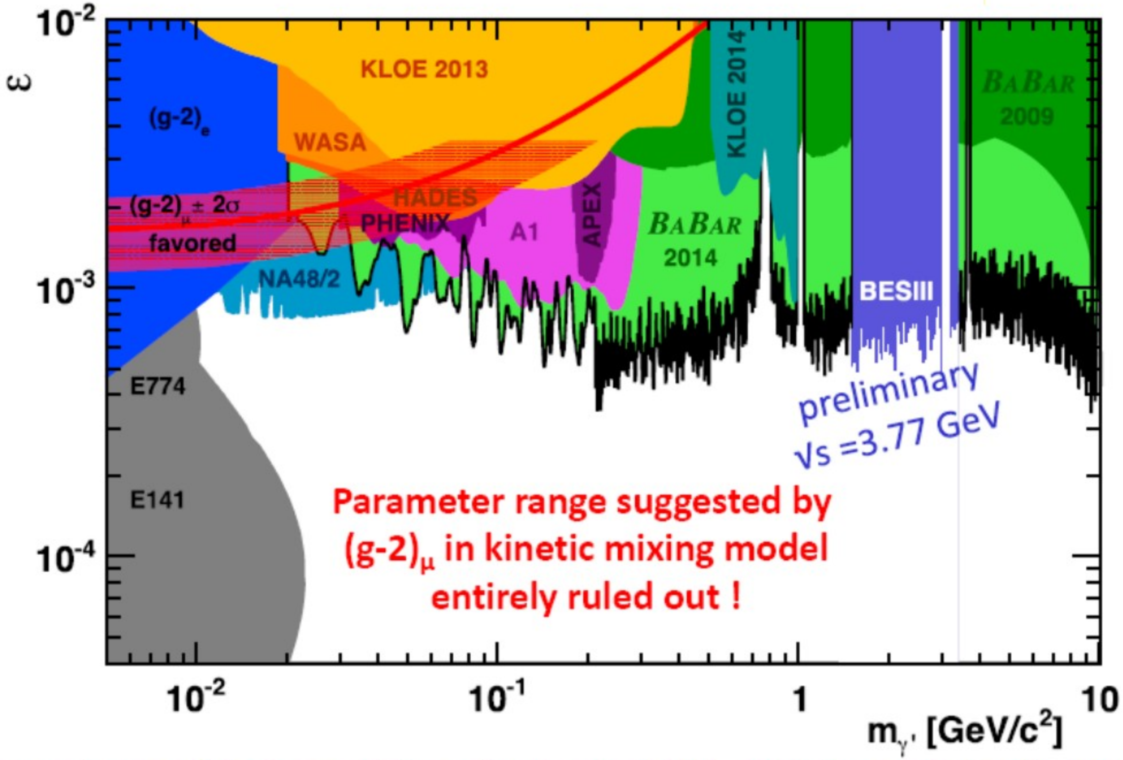


References: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.80.095024 and on **NA48/2 experiment @CERN**: here

- 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

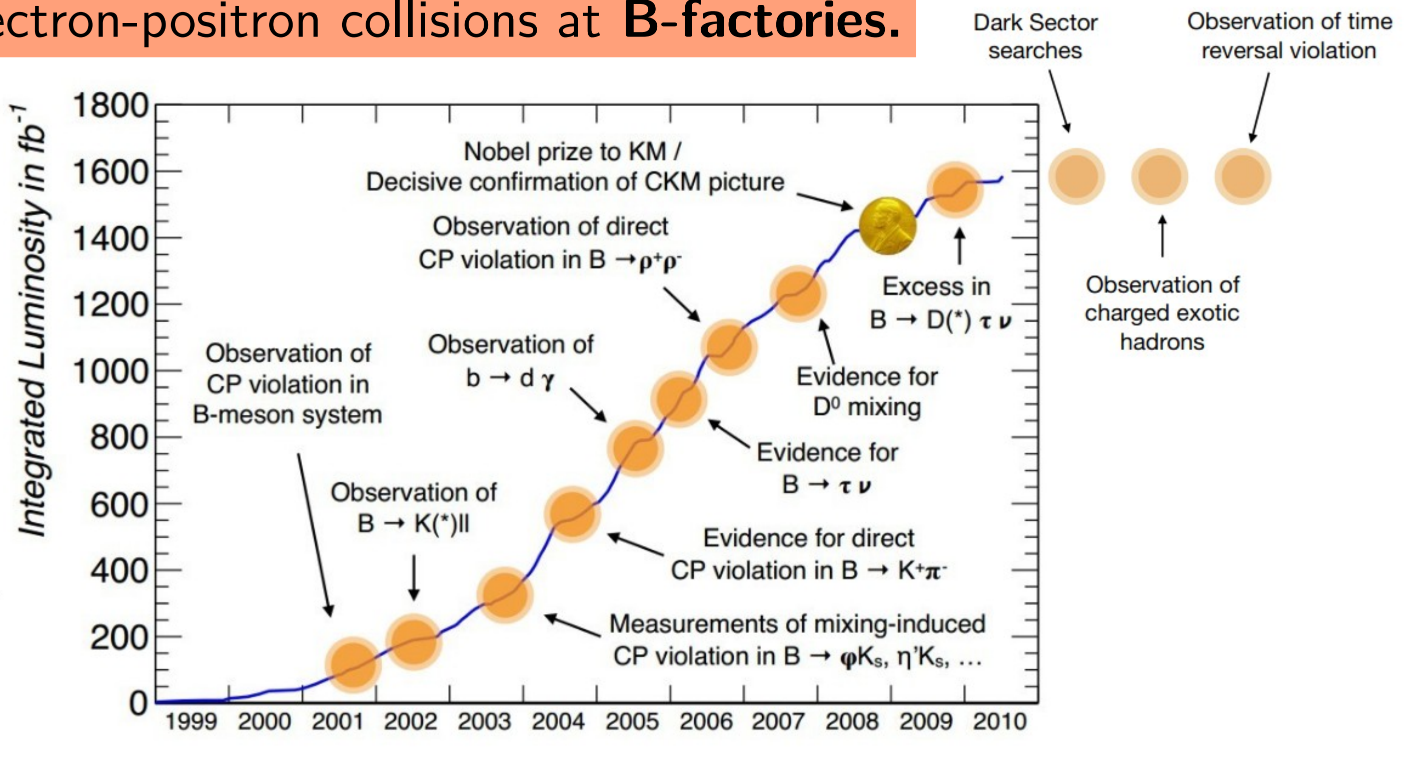


Remember: this is valid only for BR(A′→SM particles)=100%

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

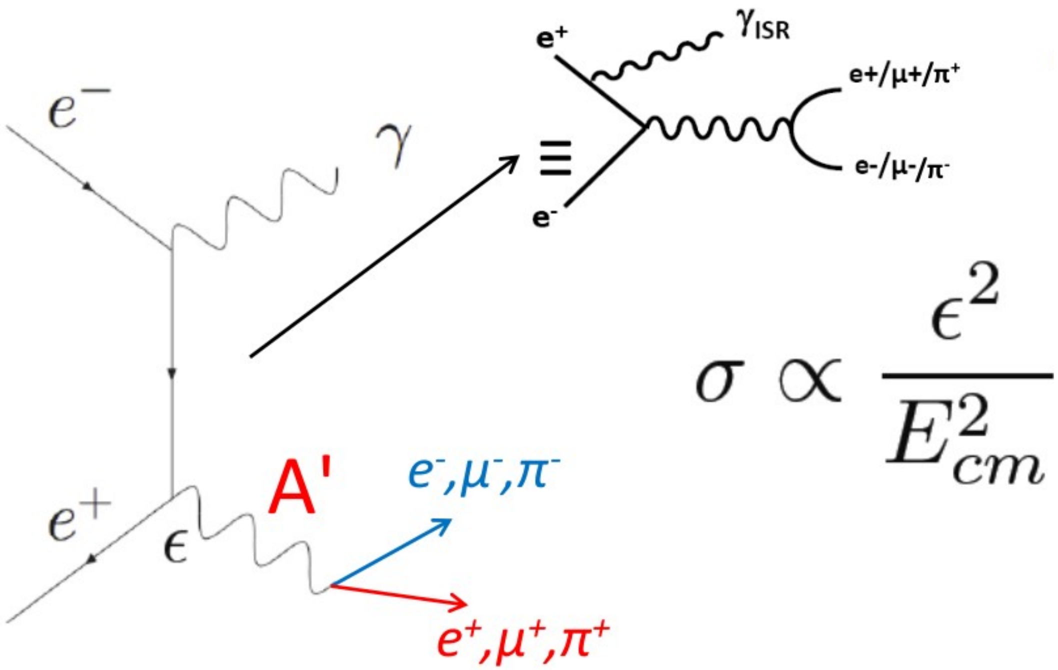
DISCLAIMER (II)

→ 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

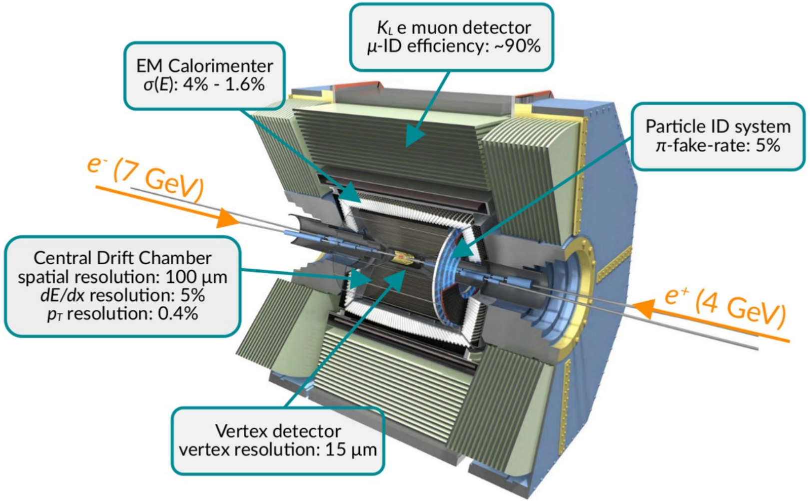


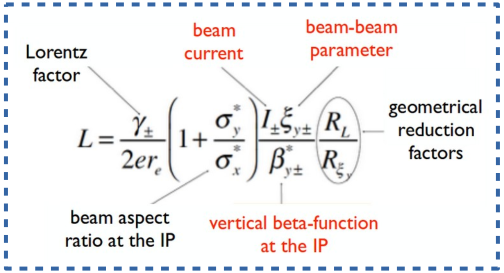
$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

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**

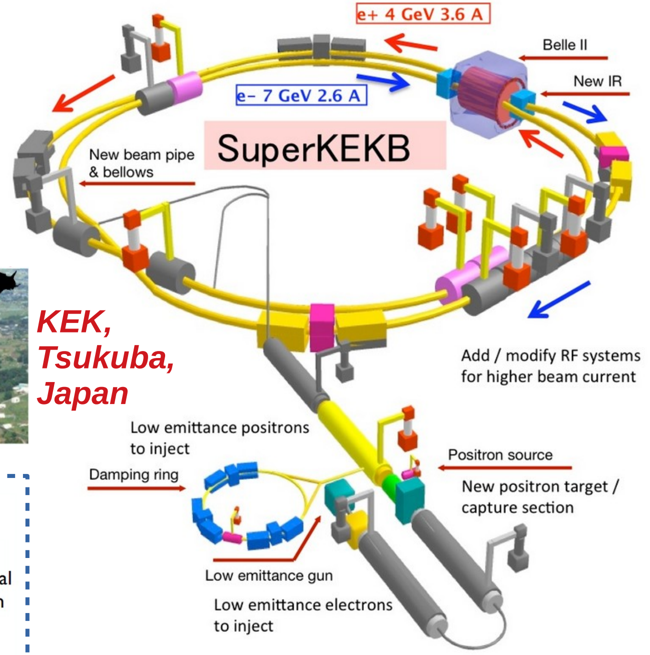




$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

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}

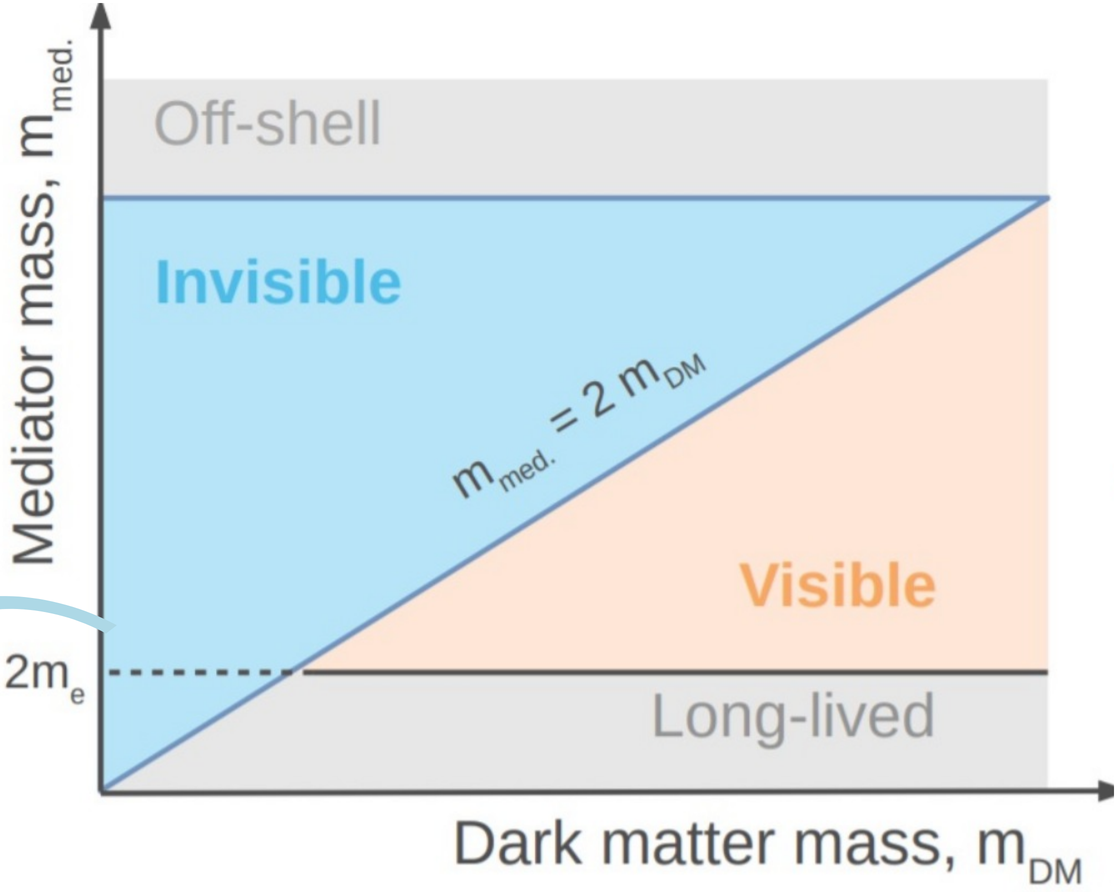
Accumulated ~0.6 ab^{-1} and unique energy scan samples during run 1 (2019-2022) and run 2 (2024 - present)

*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

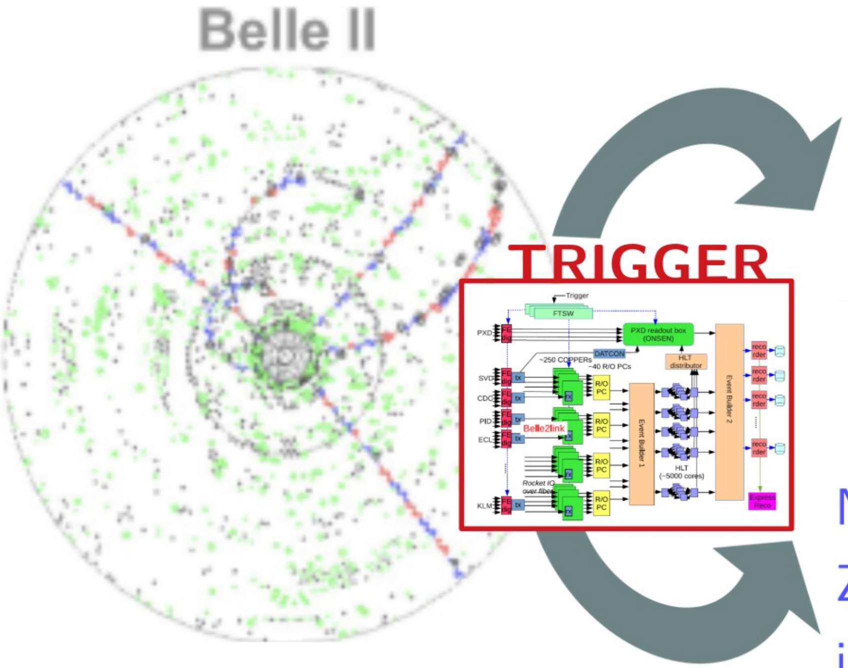


$$E_{beam}\text{-}E_{reco}=E_{miss}\ (E_{inv})$$

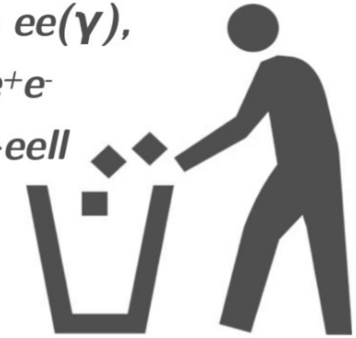
Main experimental requirements: triggers

- 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)

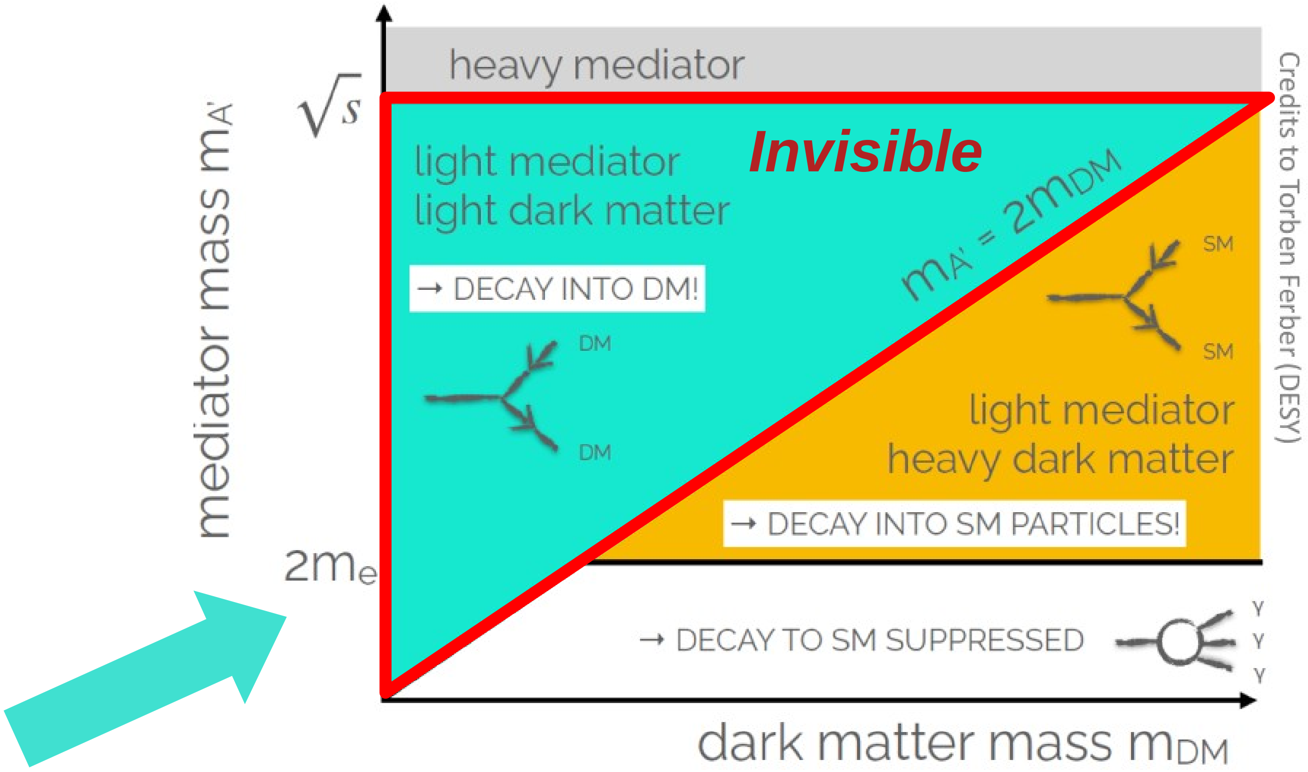


SM QED: $e^+e^- \to ee(\gamma)$, $e^+e^- \to \mu\mu(\gamma)$, $e^+e^- \to \tau\tau(\gamma)$, $e^+e^- \to eell$



NEW PHYSICS: Z' , A'$\to$ ll, A' $\to$ invisible , a $\to \gamma\gamma$

Searches for invisible decays of new mediators



Example:
Z' → invisible (2018)

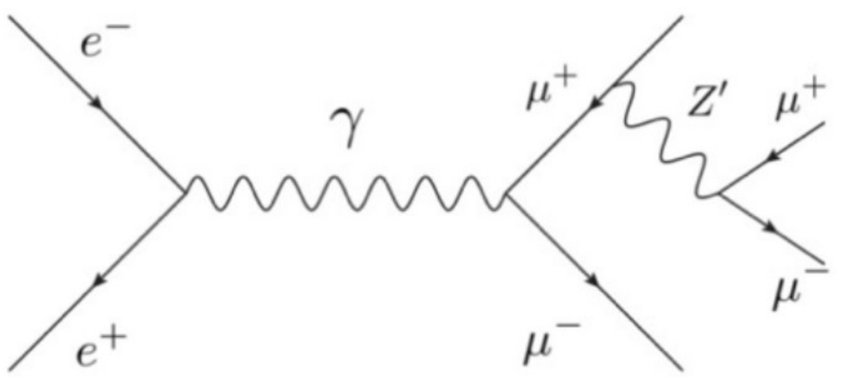
- Z' → invisible
- Dark higgstrahlung
- Single photon search

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: $e^+e^- \to \mu^+\mu^- Z'$

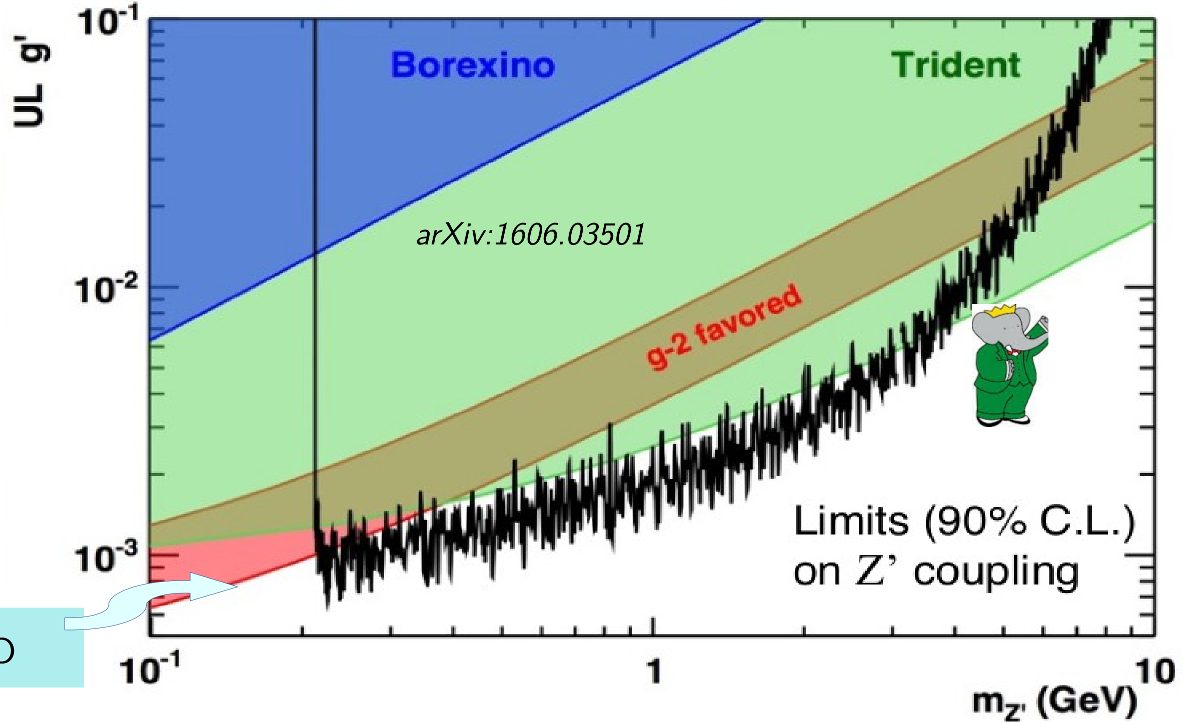


Example:
Z' → invisible (2018)

Muonic dark forces: previous results

- Existing limits on the Z' coupling (g'):
  - searches for visible decays $Z' \to \mu^+\mu^-$ (BaBar *arXiv:1606.03501*, CMS *arXiv:1808.03684*)
  - neutrino-nucleus scattering processes (*neutrino trident production,* CCFR experiment at Fermilab)

➔ Muonic dark force at BaBar: search on 514 fb^{-1} for a peak in the dimuon invariant mass distribution in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ processes

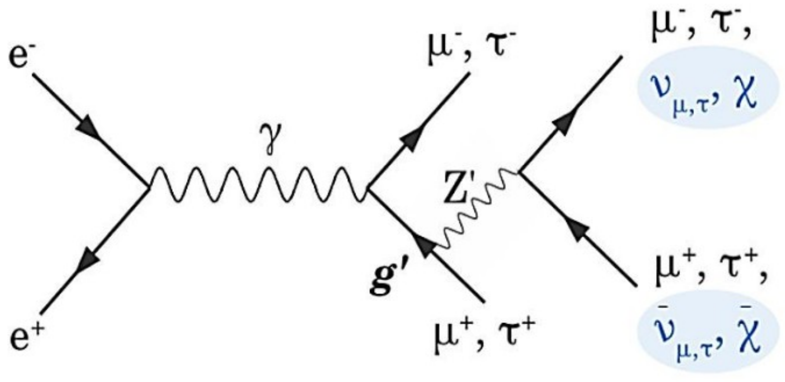


Phase space for $m_{Z'} < 2m_\mu$ UNEXPLORED

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.



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

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

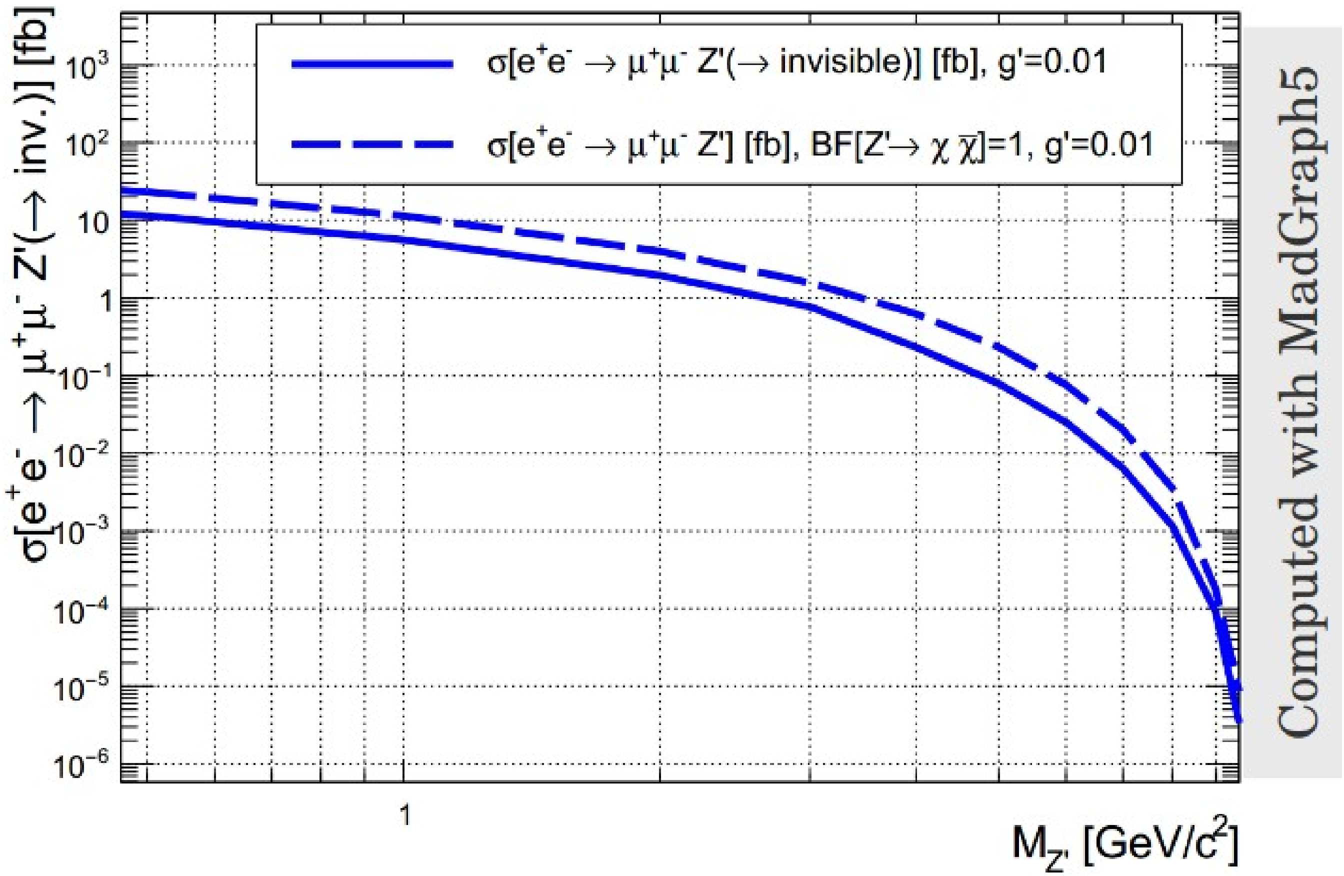
Branching ratios:

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

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

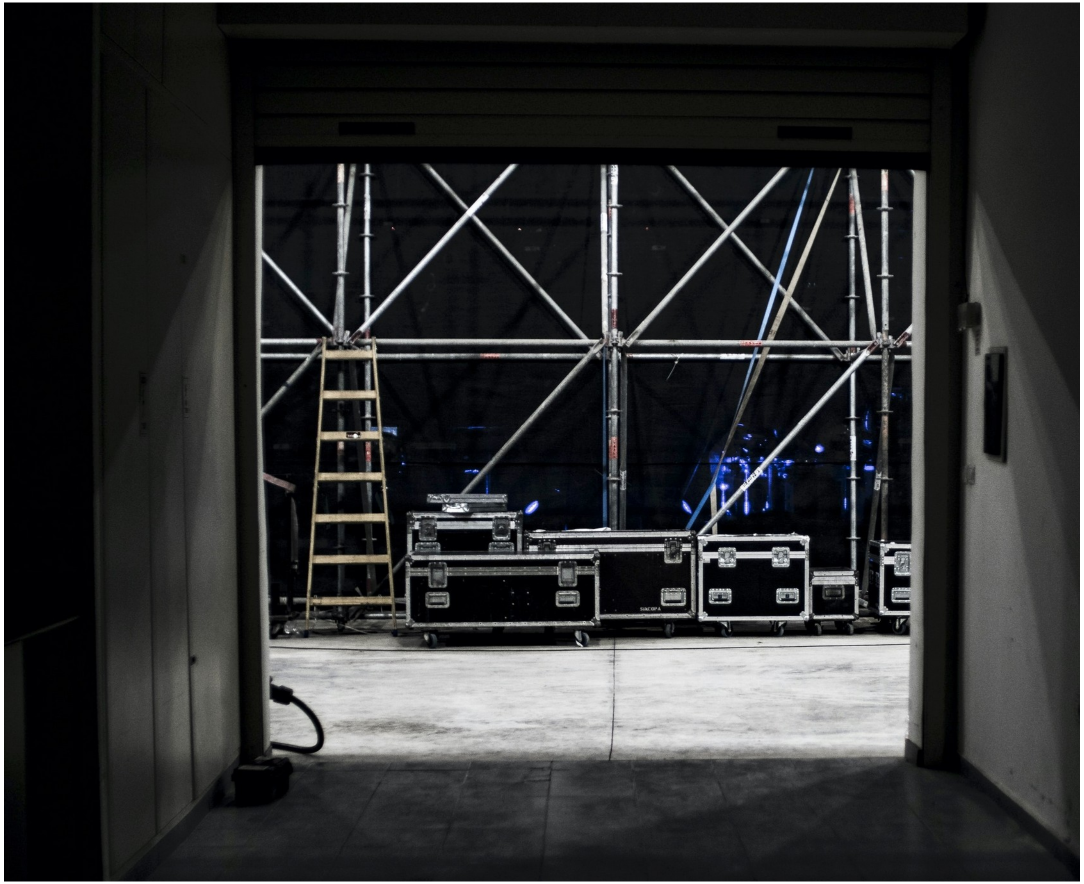
Example:
$Z' \to$ invisible (2018)

Z' production in e^+e^- collision

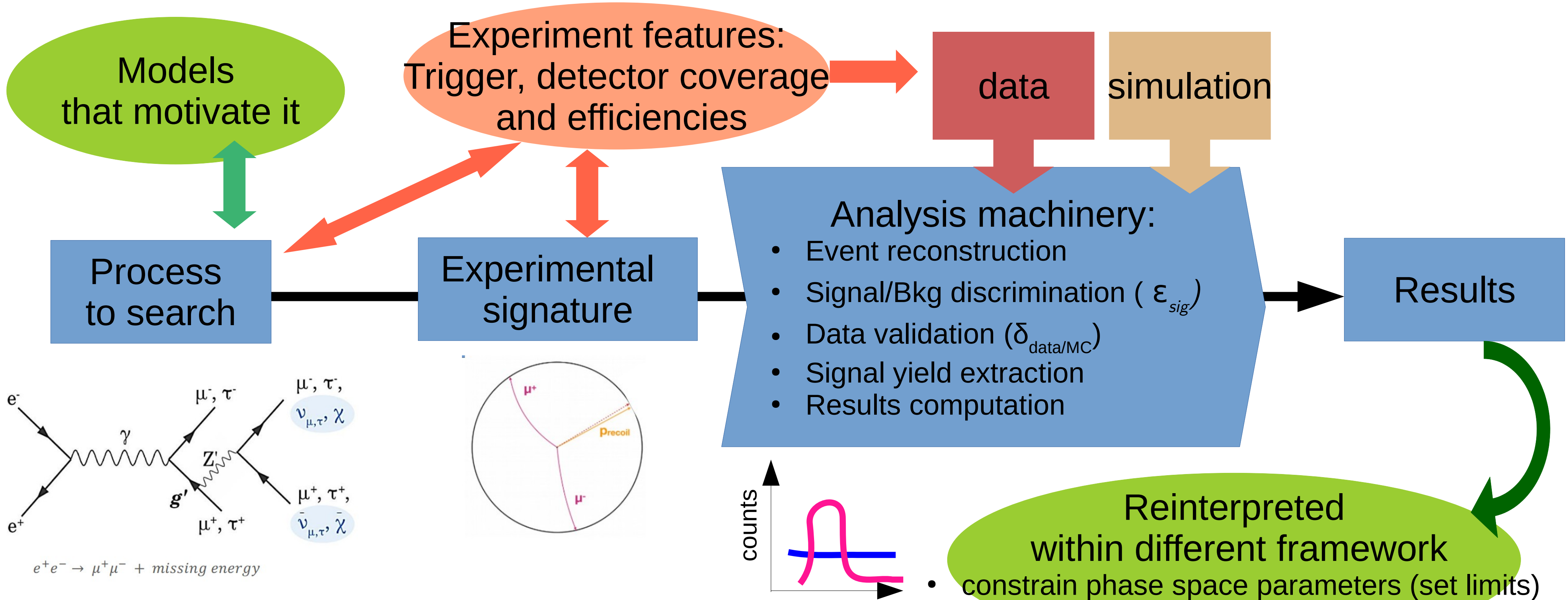


$$\sigma \propto \frac{1}{E_{cm}^2}$$

Backstage: building the analysis performance



Trailer: the plot



Lμ-Lτ model, B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004; Altmannshofer et al JHEP 1612 (2016) 106.

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:

$$M_{rec}^2 = s + M_{\mu^+\mu^-}^2 - 2\sqrt{s}(E_{\mu^+}^* + E_{\mu^-}^*)$$
$$M_{rec} = \sqrt{M_{rec}^2}, \quad \text{if } M_{rec}^2 > 0;$$
$$M_{rec} = -\sqrt{-M_{rec}^2}, \quad \text{if } M_{rec}^2 < 0.$$

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} $[10^6]$	$\int Ldt$ $[\text{fb}^{-1}]$	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)

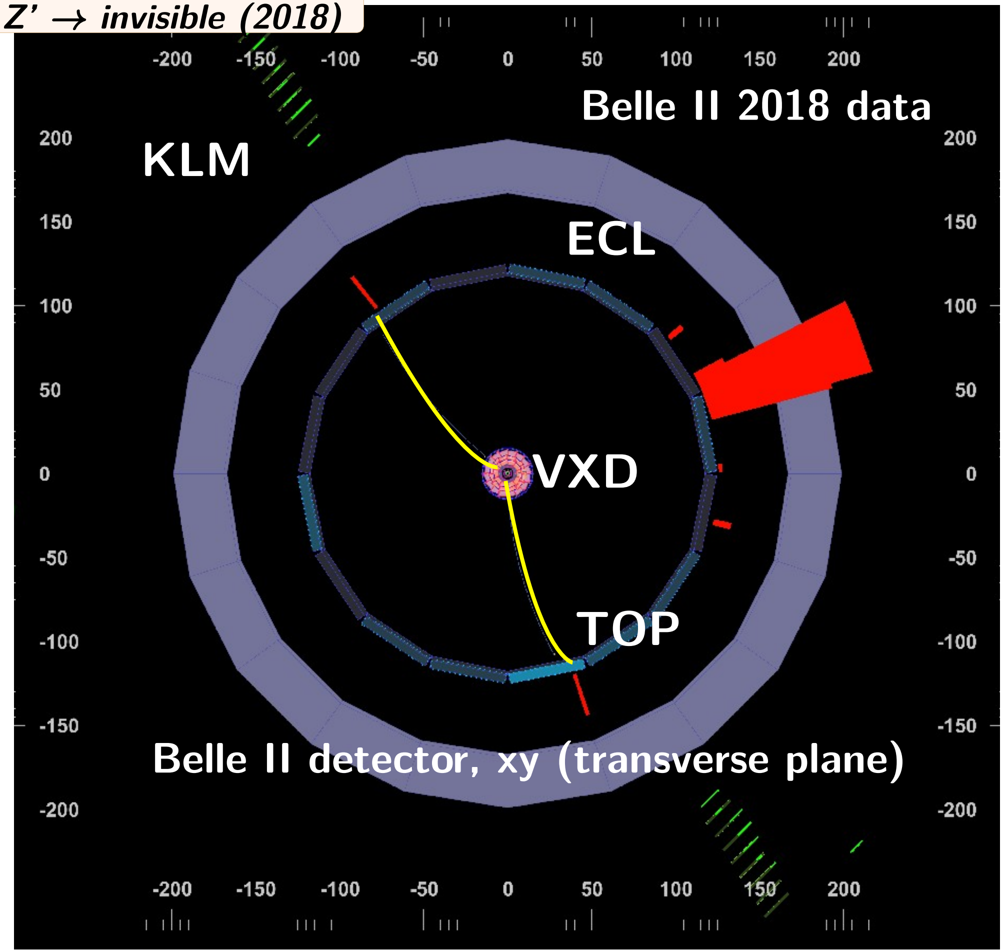
→ CAVEAT: simulation might be missing/ incomplete, mis-model the data
→ Some detector effect not simulated

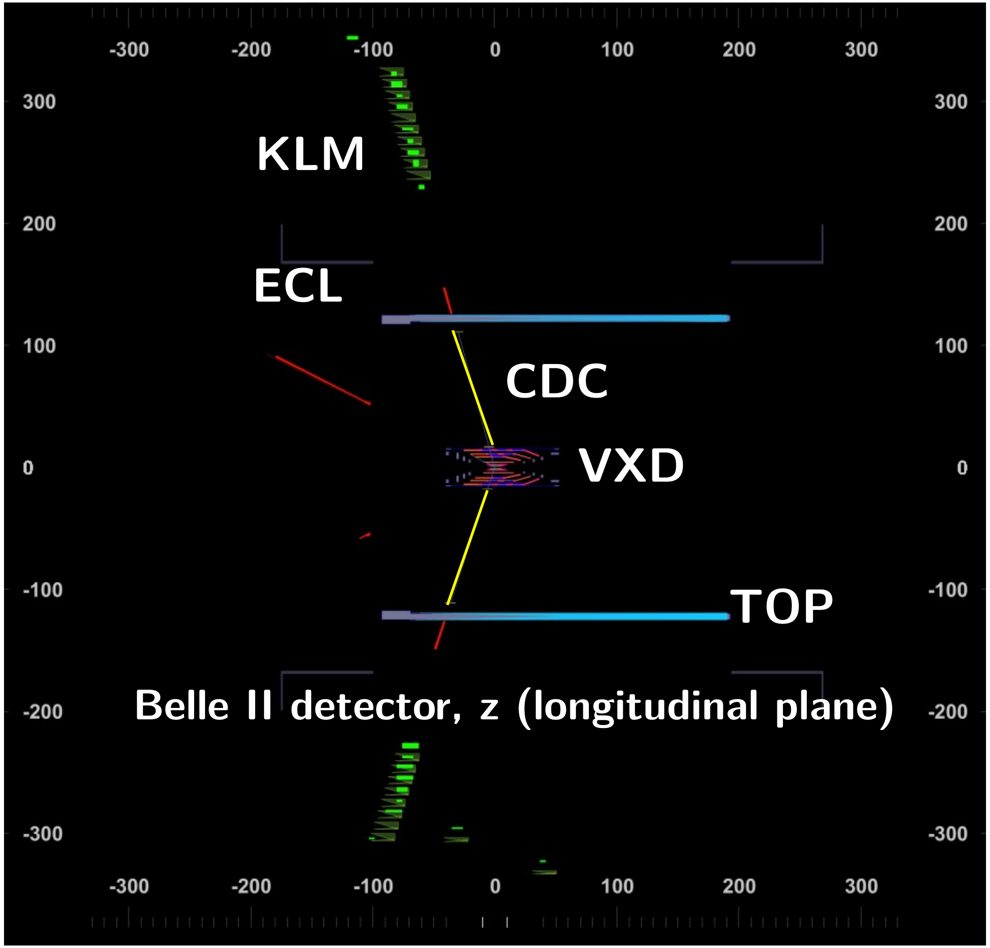
How would a dimuon event look like?

Exploit the “event display”...

Example:

Z' → invisible (2018)

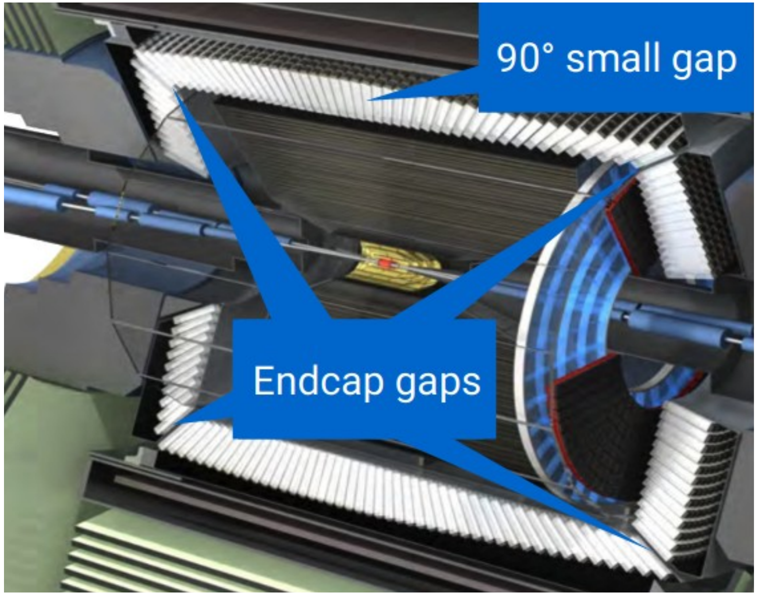




Example:
Z' → invisible (2018)

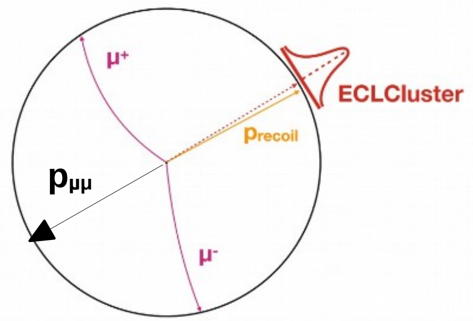
Event selection

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

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

→ revert muon selection

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

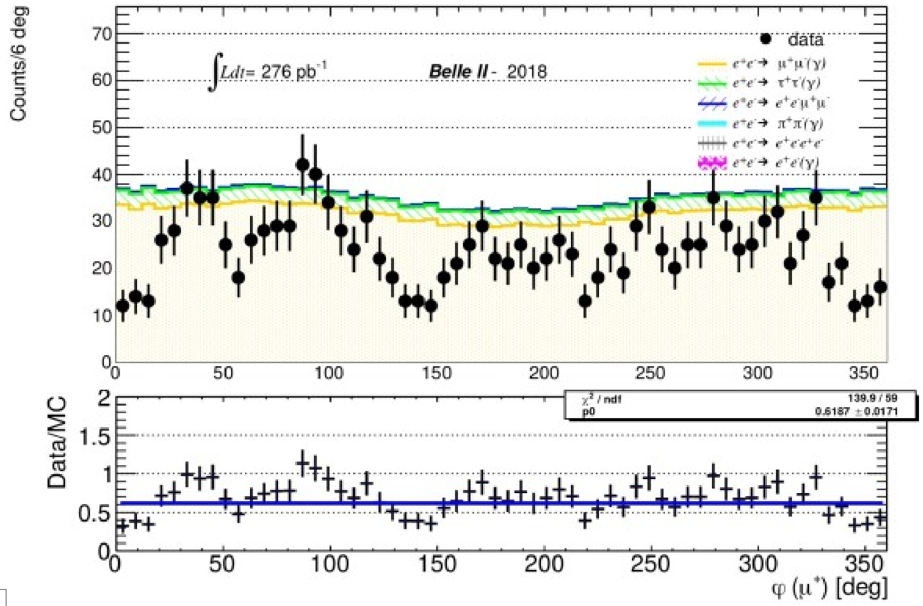
- check low recoil mass region, $M_{rec} < 3$ GeV
- validate the trigger selection

→ 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)

Detector performance studies

- Real detector != simulated detector

→ GOAL: Estimate the **discrepancy** in detector efficiencies and resolutions between data and simulation, and based on this measurement:

  - **correct** the simulation for additional effects observed in data
  - assign a **systematic uncertainty** due to the applied corrections

...for the Z' analysis, three main contributions affect the selection efficiency:

- Trigger selection
- Track reconstruction efficiency
- Particle identification selection

→ devise studies to measure the differences in efficiencies between data and simulation

Example:
Z' → invisible (2018)

Systematic uncertainties

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

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

Estimated from simulation

From other measurement

Example:

Z' → invisible (2018)

Systematic uncertainties

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

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

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.**

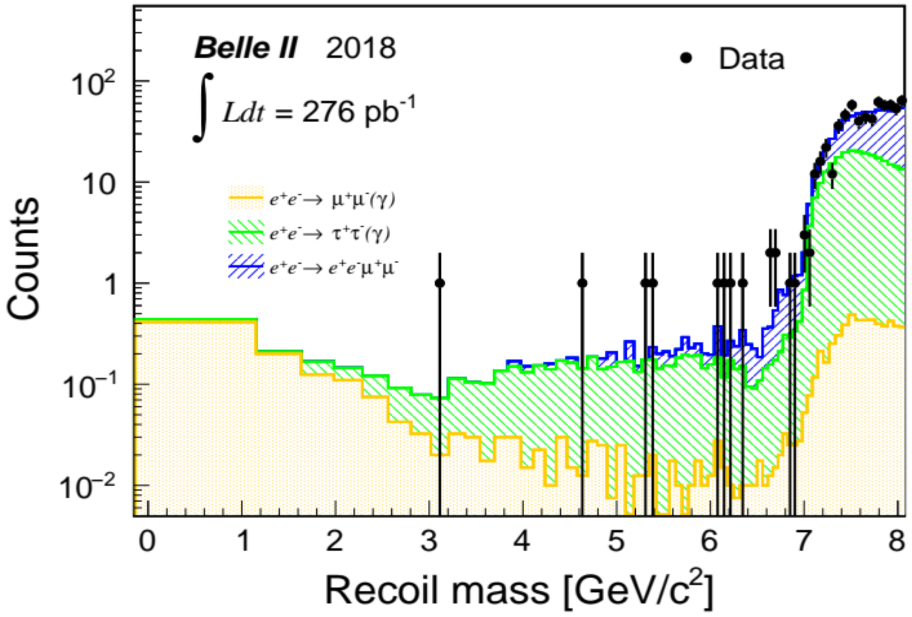
- Trigger, Tracking and Particle ID: from performance studies
- from offline luminosity measurement [arXiv:1910.05365]
- Bkg suppression impact on control sample (statistically dominated)
- Background yields: from data-MC agreement in control samples with reversed τ-suppression selection

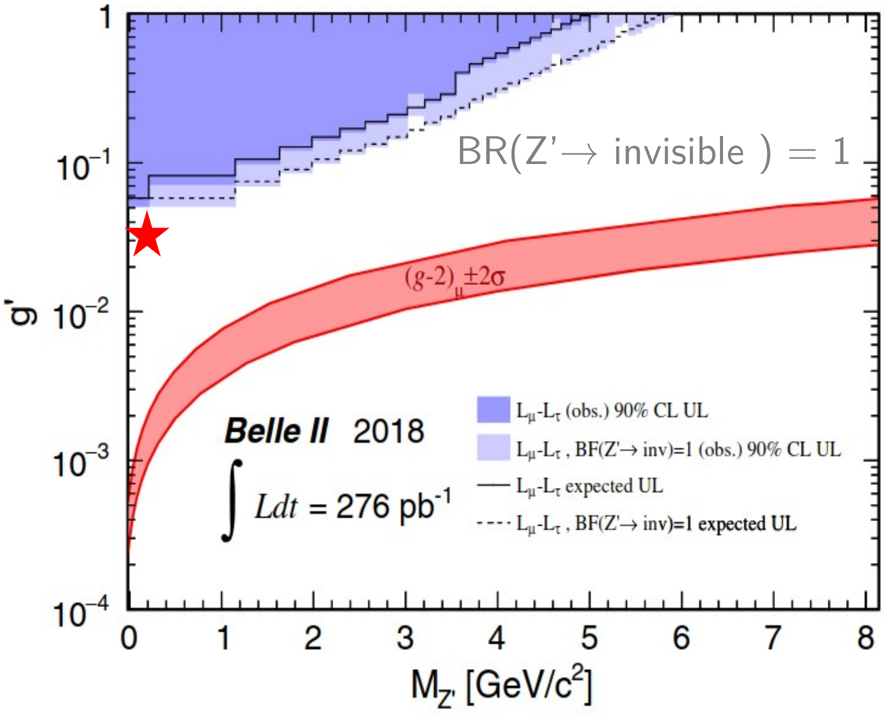
- Selection finalized
- Corrections applied and systematic uncertainties assessed from cross-check on control sample/sidebands
- Signal yield extraction and limits computation defined

Time to unboxed the data and compute the results!

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...

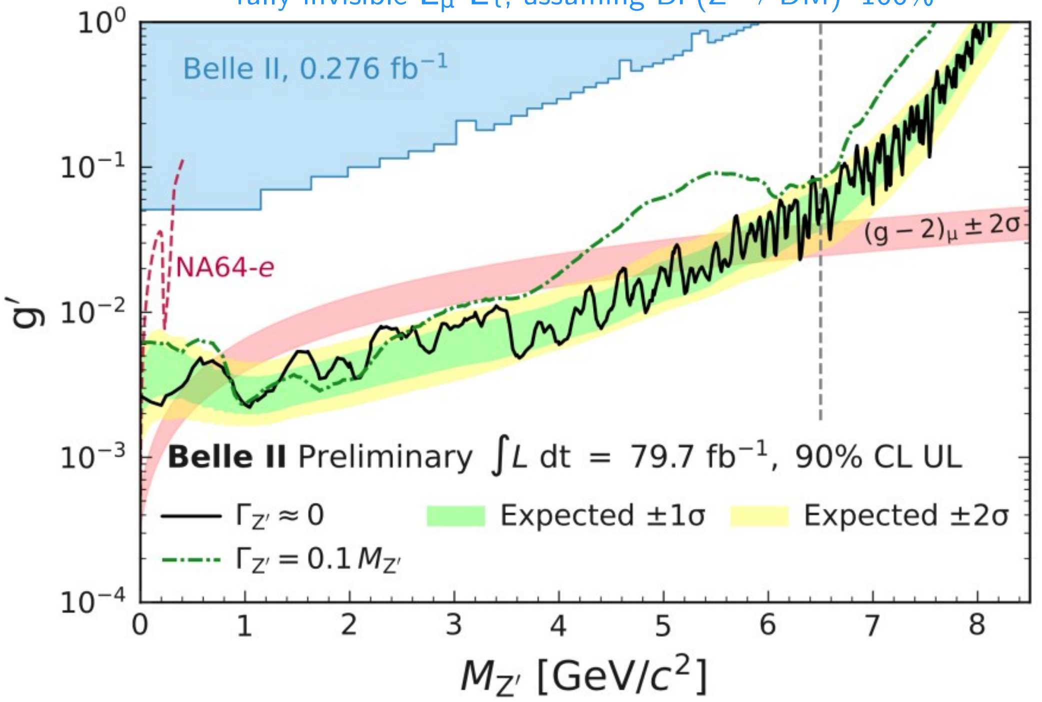
New limits on invisible Z'

Update on 2019-2020 data:

- 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%

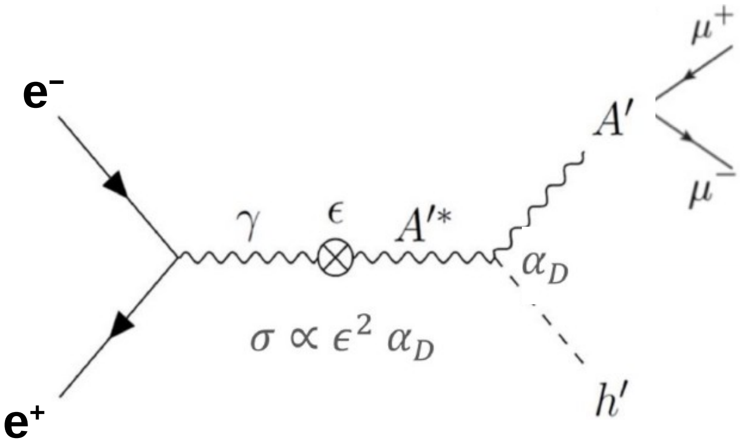


IMPROVEMENT: $(g\text{-}2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5$

Inheriting from Z' $\rightarrow$ 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, **$e^+e^- \rightarrow A'^* \rightarrow h' A'$**

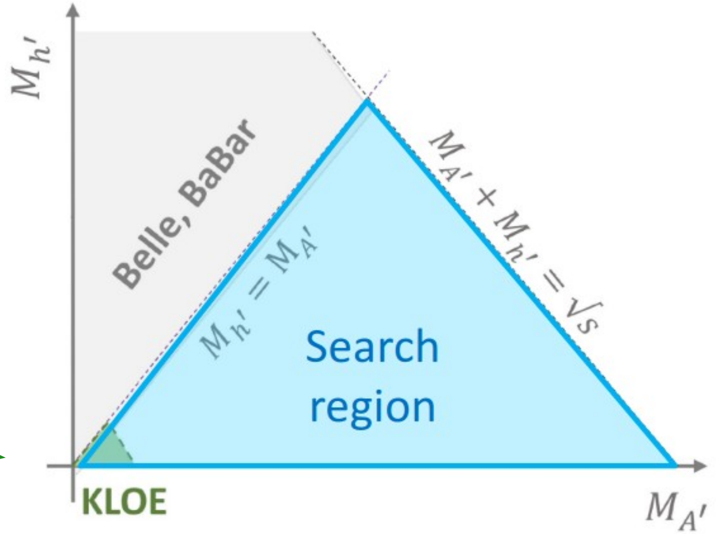


- 4 parameters (no mixing with SM Higgs assumed): $\boldsymbol{m_{h'}}$, $\boldsymbol{m_{A'}}$, **ε, $\boldsymbol{\alpha_D}$**
- $M_{h'} > M_{A'}$: *h' can decay to a pair A', and A' into SM final states, "visible dark higgs"already searched by Belle, Babar*
- $M_{h'} < M_{A'}$: ***invisible*** *decays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

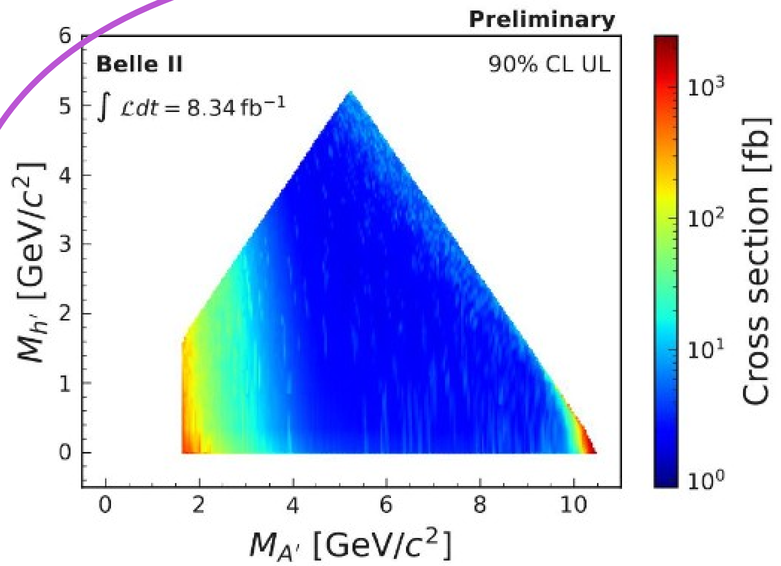
Use also direct mass $M_{\mu\mu}$ → expected to peak at A' mass

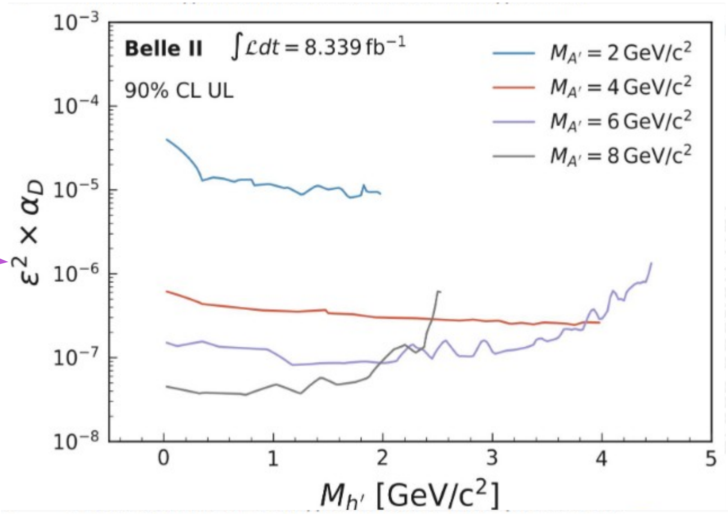
- 2D plane search ($M_{\mu\mu}$, M_{rec})

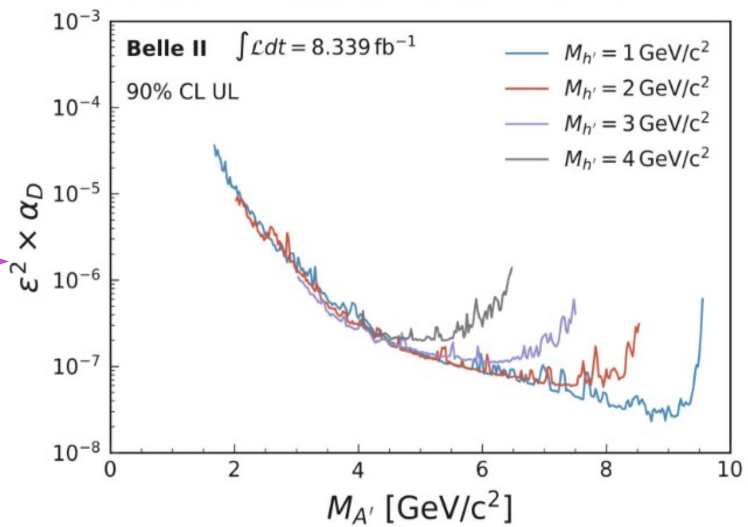
* Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

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

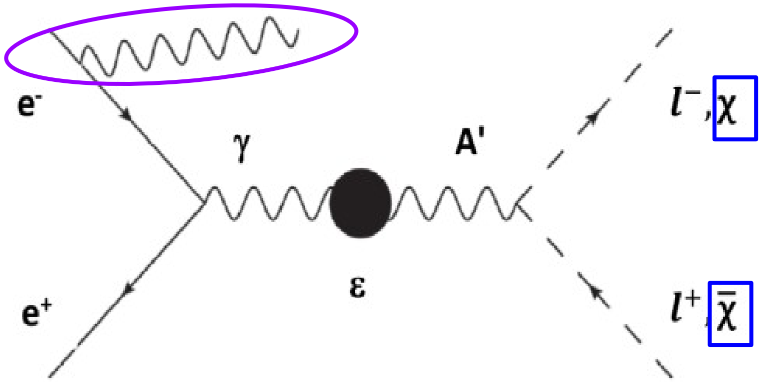
(e.g., long-lived higgs mixing with h_{SM})

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

Single photon search

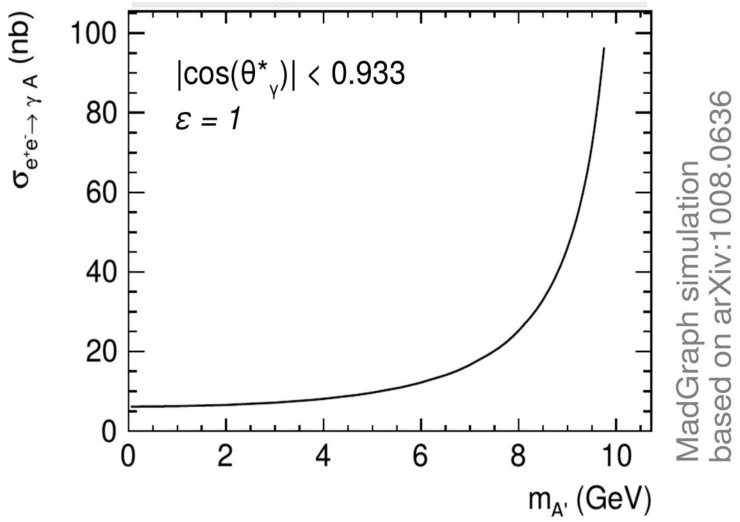
- At e^+e^- colliders investigate the ISR production $e^+e^- \rightarrow \gamma\ A'$.

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



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

Batell et al. (2009), arXiv:0903.0363

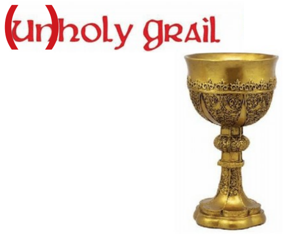


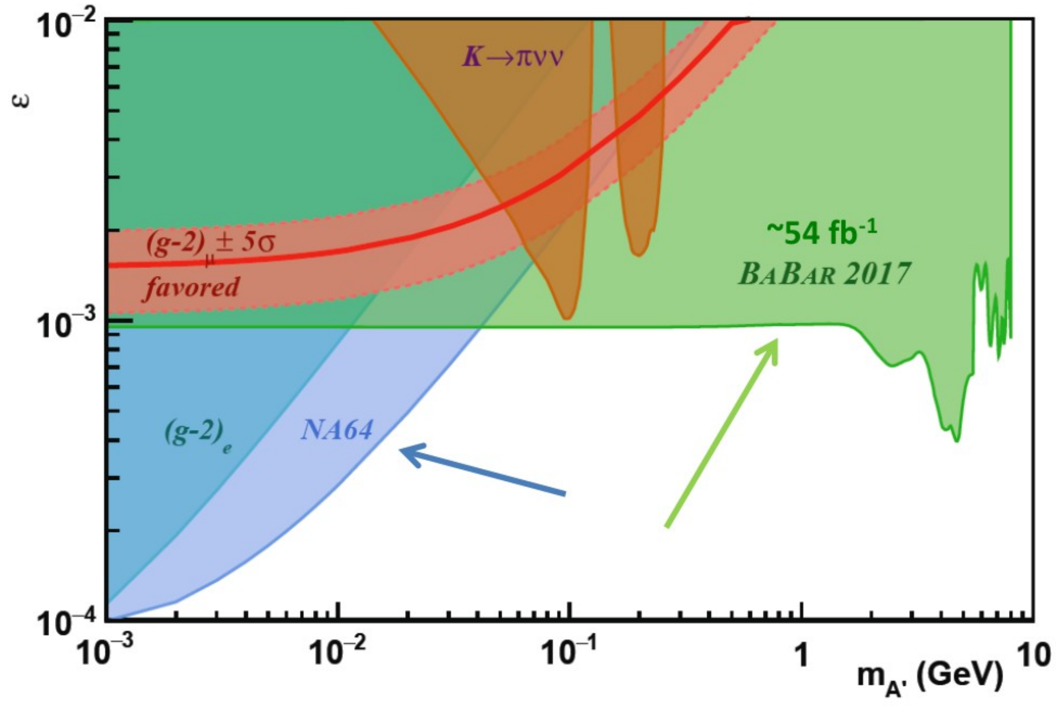
- Select events with **nothing** but a single high energetic *ISR photon.* Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

(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

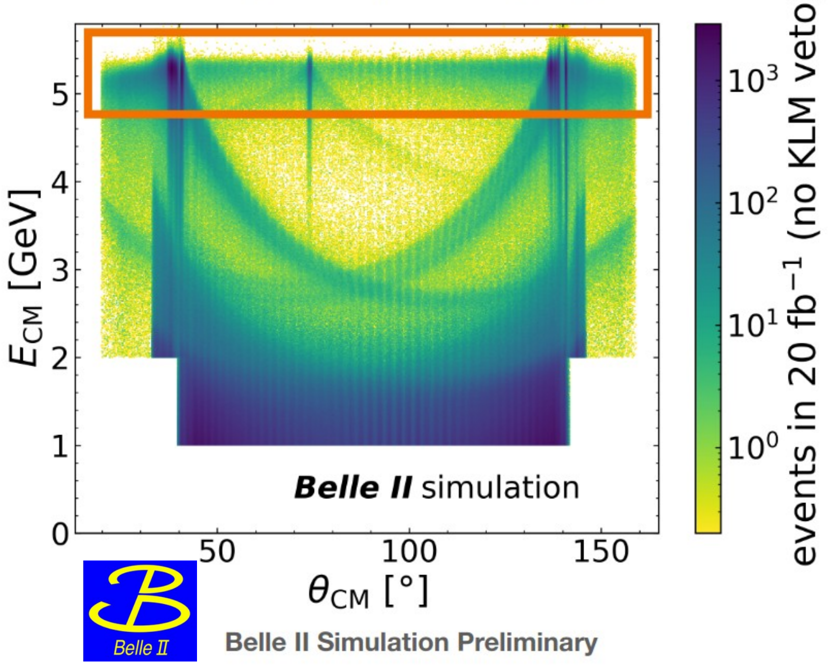
Single photon search



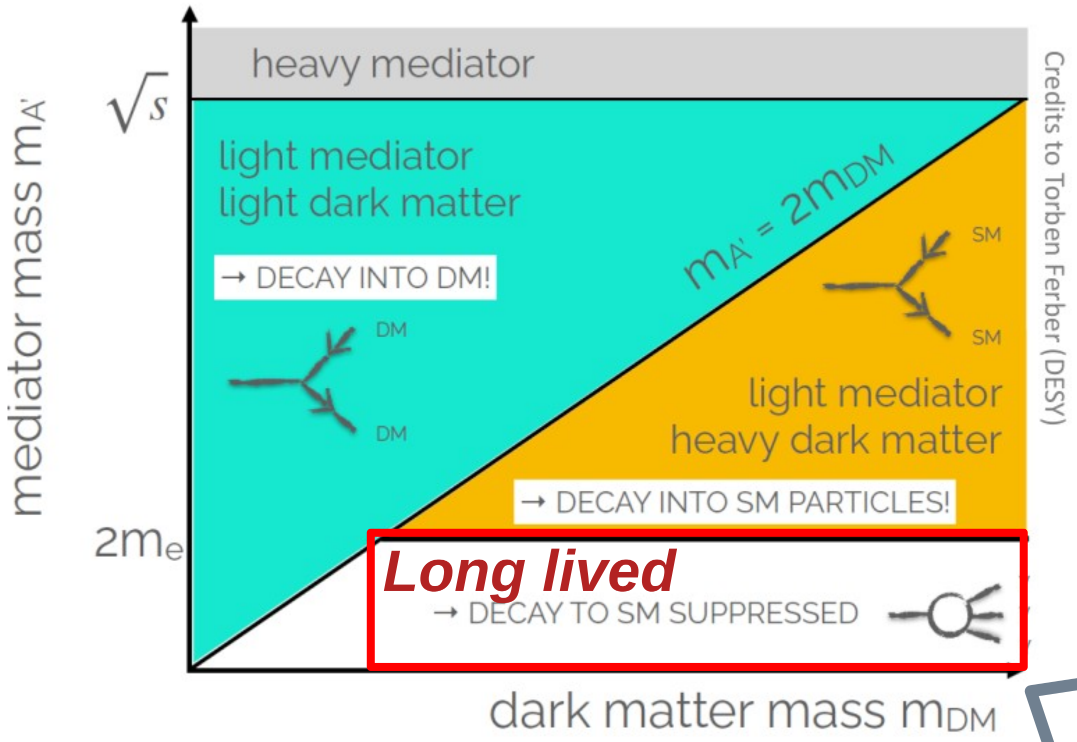


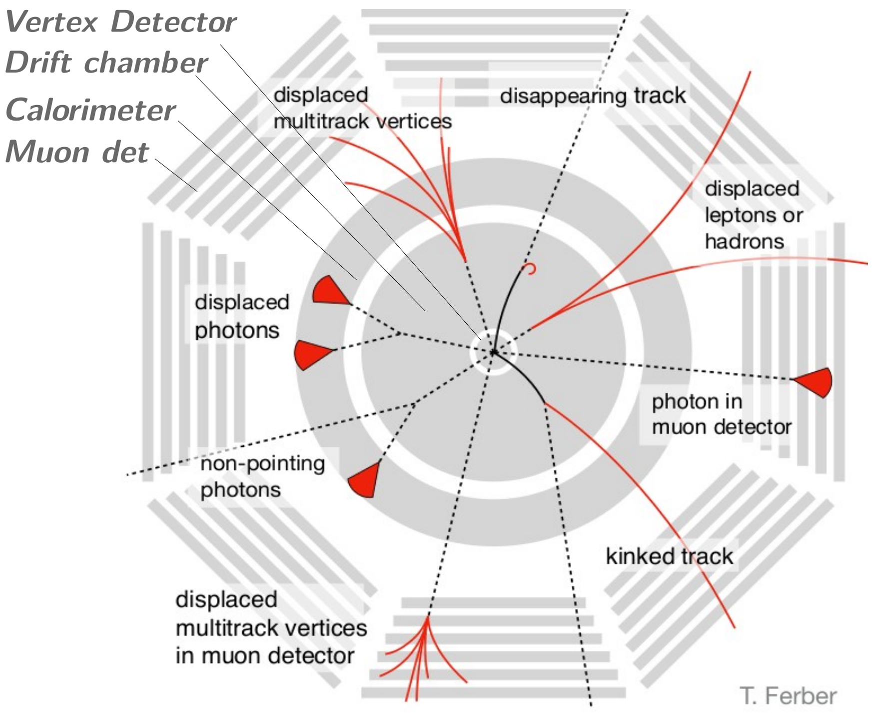
Crucial to devise photon veto to compensate for detector inefficiencies that could mimic monophoton signal

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



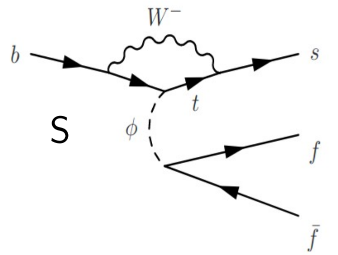
Displaced vertices at Belle II



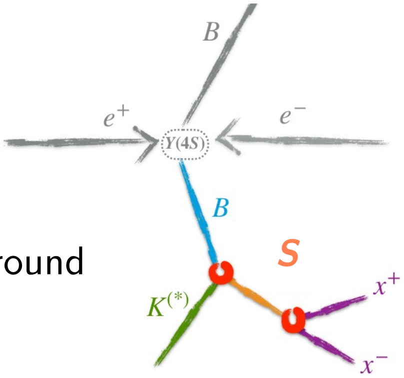


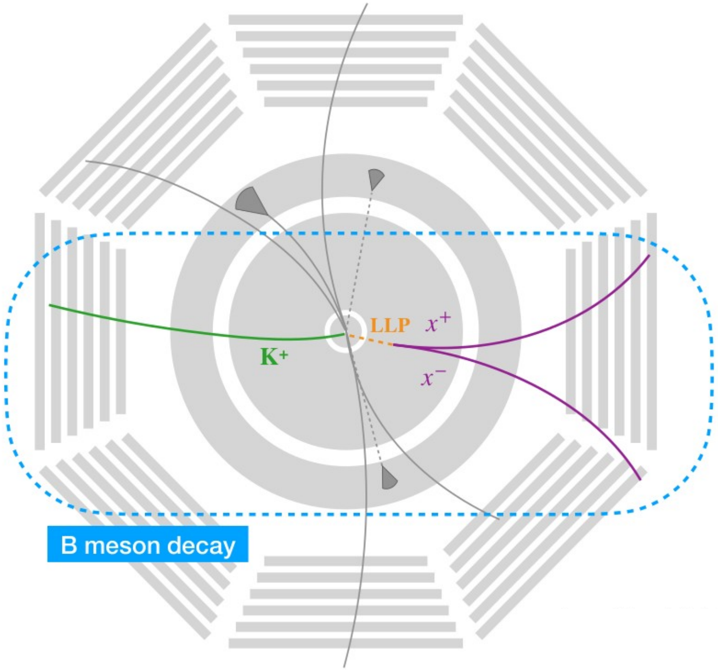
Search for long-lived (pseudo)scalar in b→s transitions

- **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

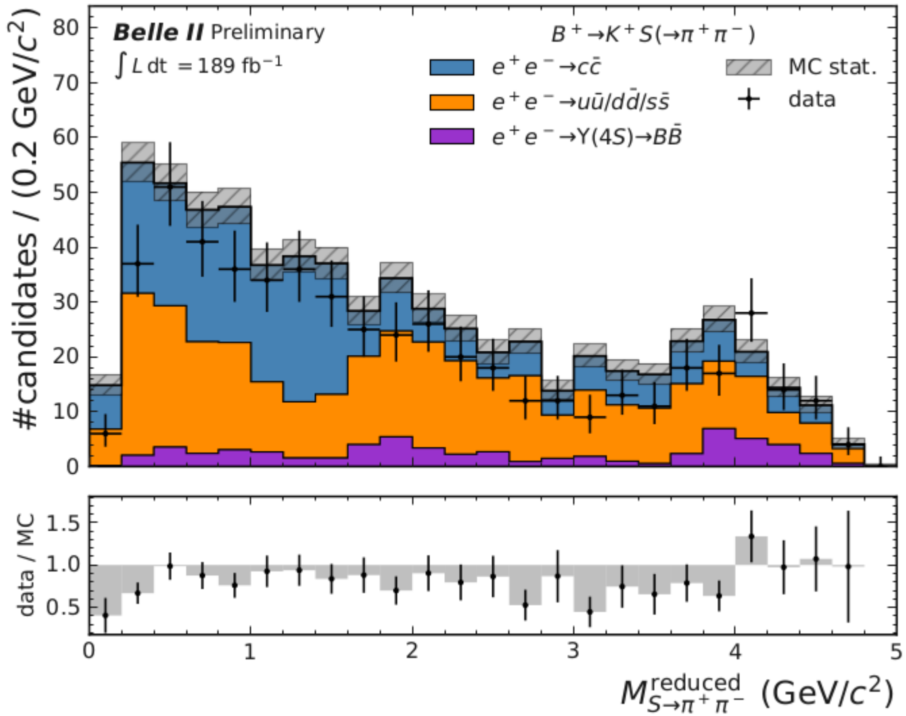




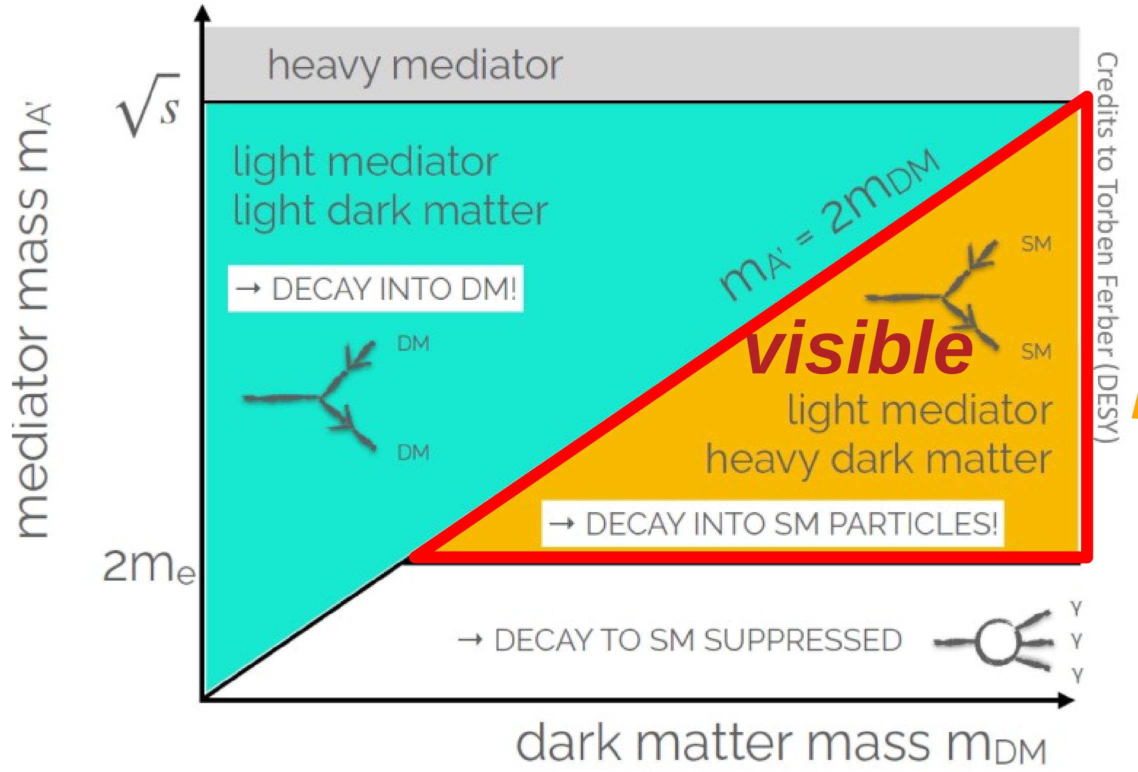
Background estimate

$$M^{\text{reduced}}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$$

- Look for a **narrow peak** in distribution of the invariant **mass spectrum**
  - extended max likelihood unbinned fits with template PDFs for signal (modeled on simulation, yield floating) + bkg (also shape fitted from the data)
  - separately for each channel and lifetime
- Peaking bkg: SM long-lived $\mathbf{K_s}$ **mass region vetoed**
  - used as control sample in data to validated displaced vertex efficiency and evaluate the systematic uncertainties



Searches for visible decays



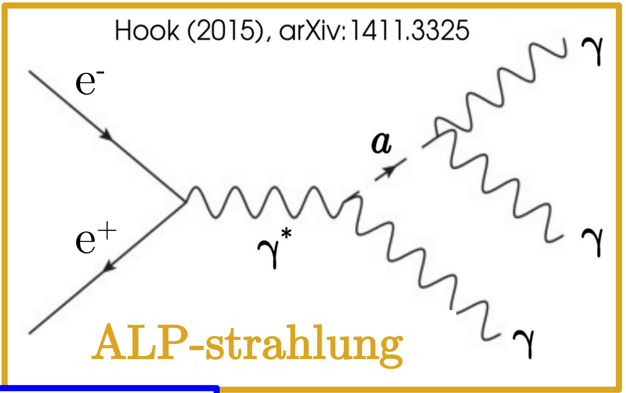
- ALPs to photons

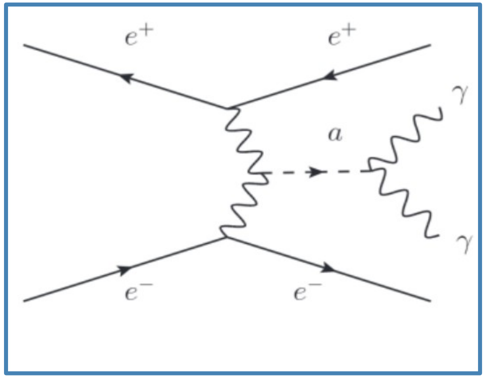
Exploring pseudo-scalar portals: ALPs

Axion-like particles

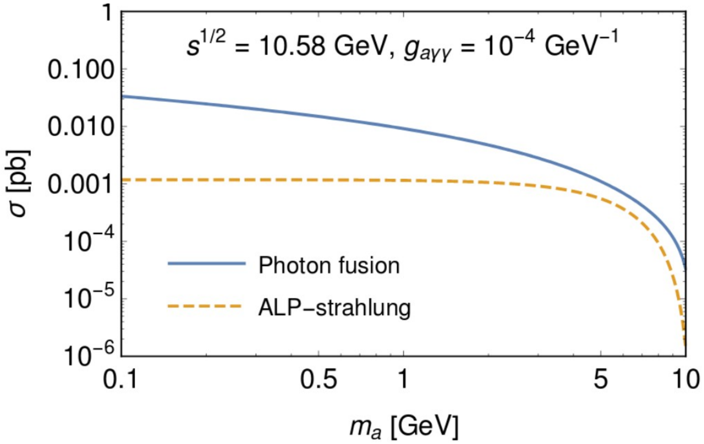
- Axion-like particles (ALPs) are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants $[g_{aV}] \sim 1/M$
- Explored photon coupling $g_{a\gamma\gamma}$ in ***ALP-strahlung* processes**

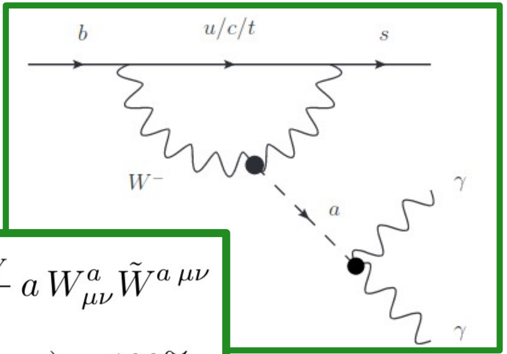
  → *photon fusion* sensitivity limited by irreducible $e^+e^- \to \gamma\gamma$ background
- Possible to investigate g_{aW} coupling in neutral current processes (rare B meson decays): **B→Ka**





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

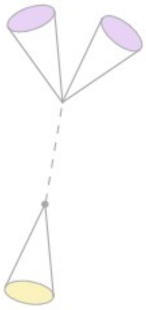




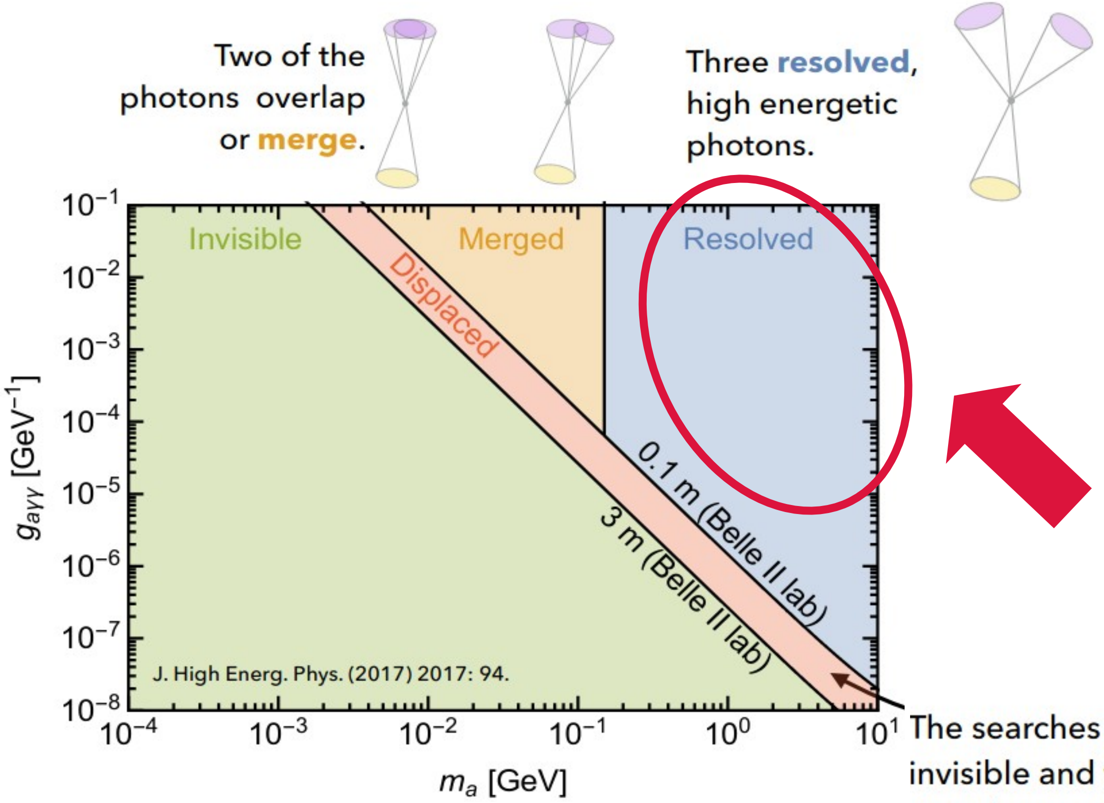
$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

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

ALP-strahlung: $a \to \gamma\gamma$ search



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



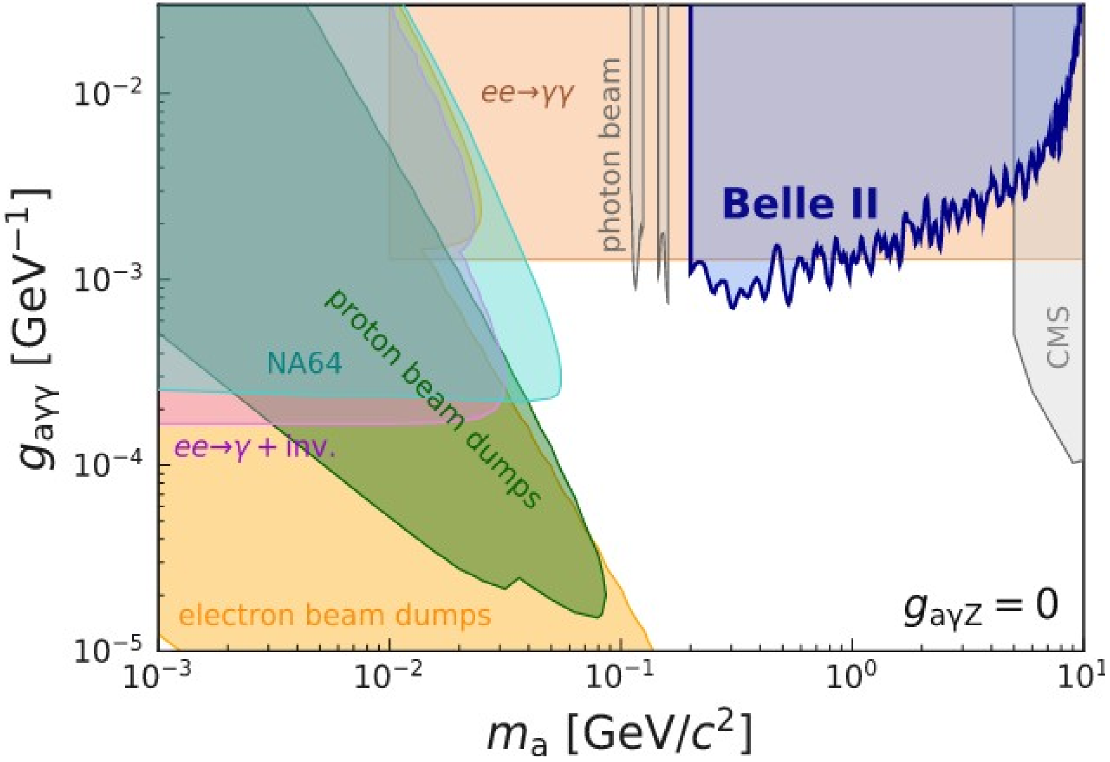
The searches for invisible and visible ALP decays veto this region.

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

$a \to \gamma\gamma$: existing limits

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

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



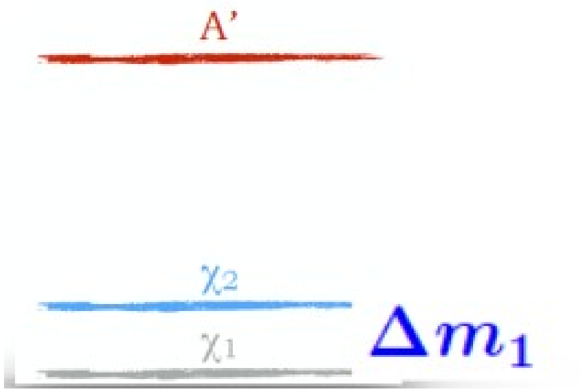
PRL 125 (2020) 161806

Rich dark sectors: non-minimal model testing

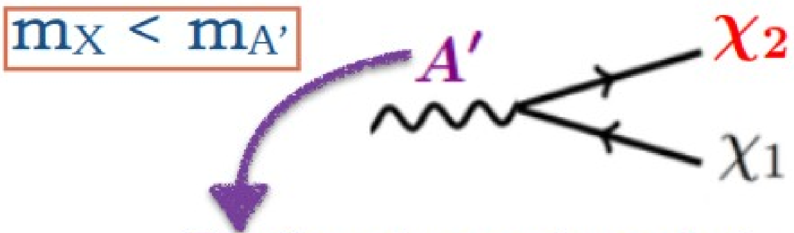
Inelastic dark matter

- 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)

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

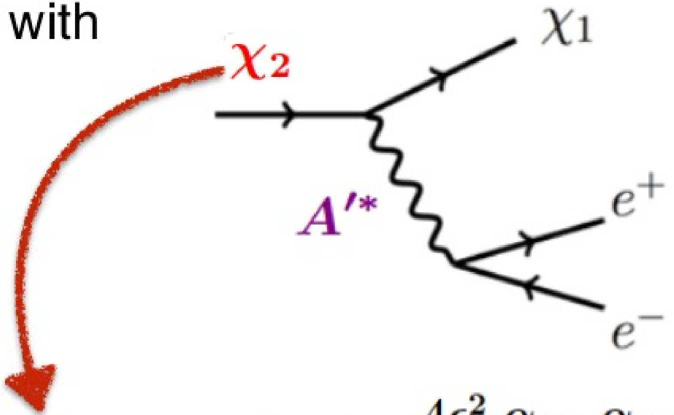


Inelastic dark matter decays



Copiously produced at high intensity experiments

with



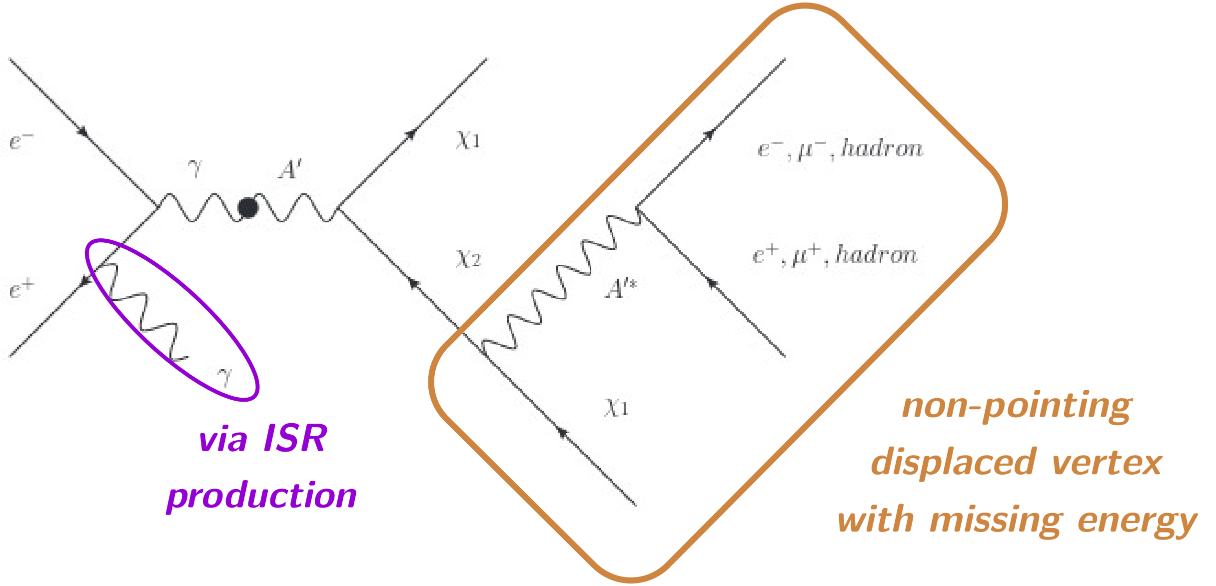
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2 \, \alpha_{\rm em} \, \alpha_D \, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

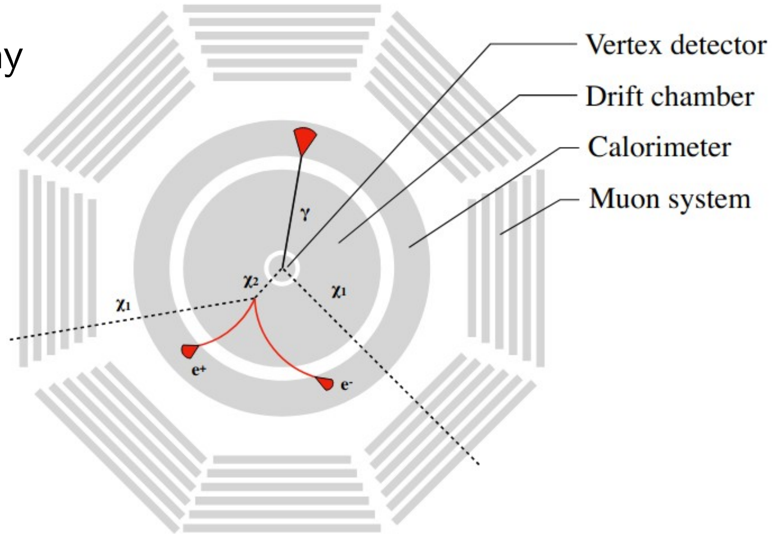
→ unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed

high intensity experiments are the prime avenue to probe IDM!

IDM signatures

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





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)

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

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

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
- Belle II has unique or world leading reach in many searches
  - Important complementarity with present and future fixed-target experiments

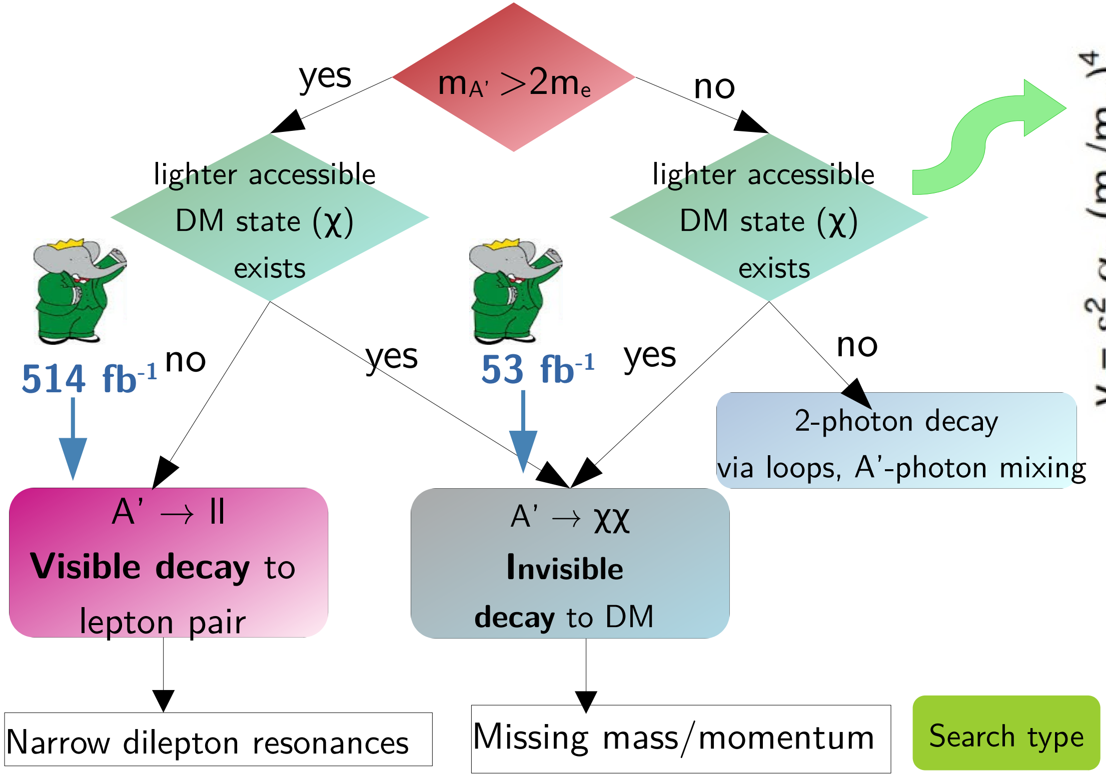
References:

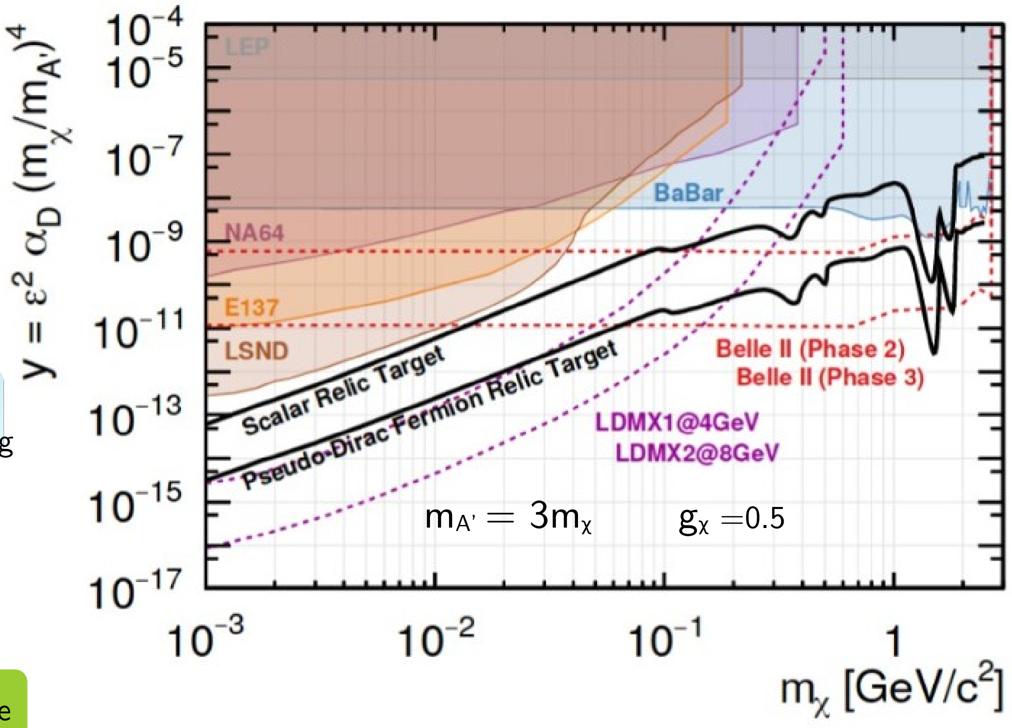
- Dark Sector Studies with Neutrino Beams (Snowmass Whitepaper)
- Snowmasss 2021 RF6 Dark Sector Physics Report

- 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





The Belle II Physics Book, PTEP 2019 (2019)

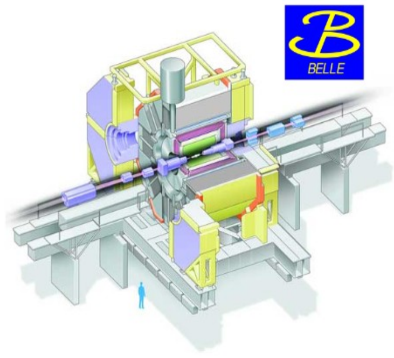
Experiments at B-factories

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

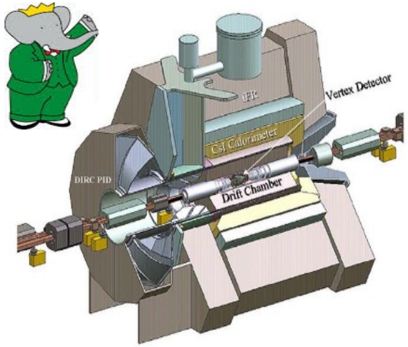
$$e^+e^- \rightarrow \sqrt{s} = 10.58 \text{ GeV } (\Upsilon(4S)) \rightarrow B\bar{B}$$

$\Upsilon(nS)$ = 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

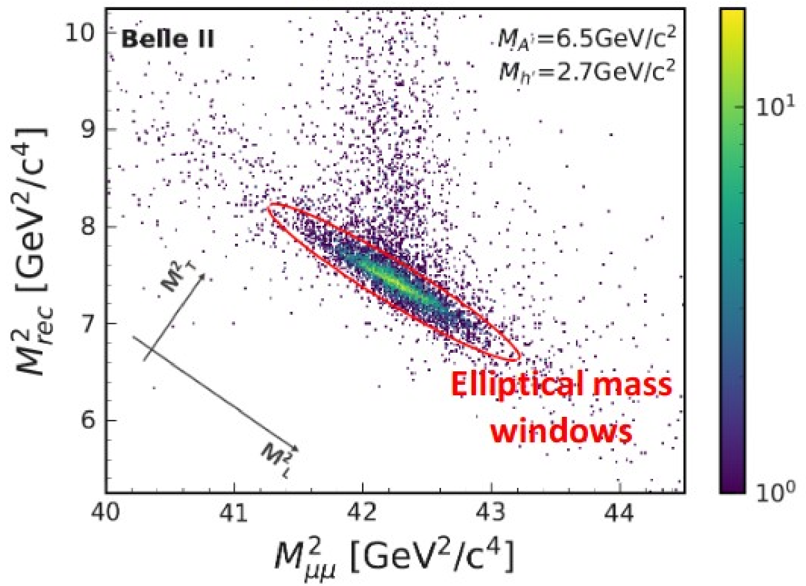
Dark higgsstrahlung: analysis strategy

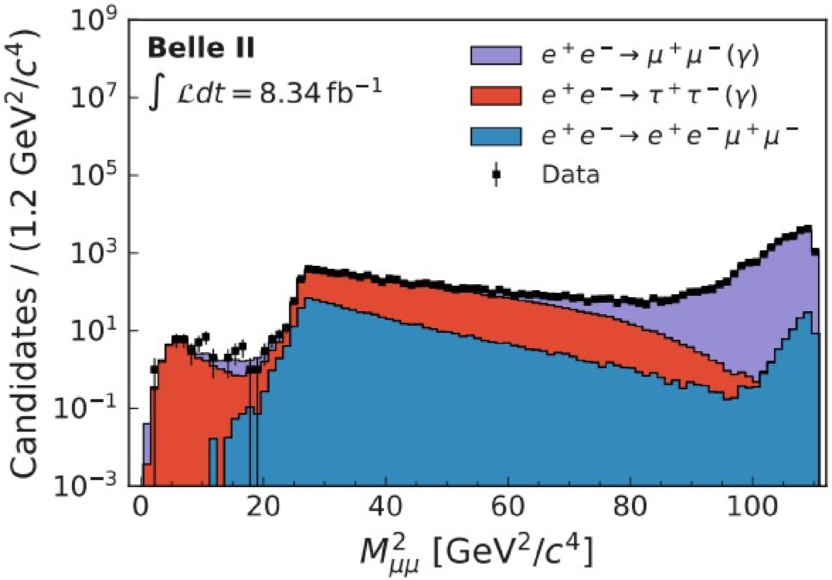
- A' reconstructed as muon pairs, $M_{\mu\mu} > 1.65$ GeV for trigger requirements

  $\rightarrow$ *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)

$\rightarrow$ Final recoil spectrum in good agreement between data and simulation

Signal simulation

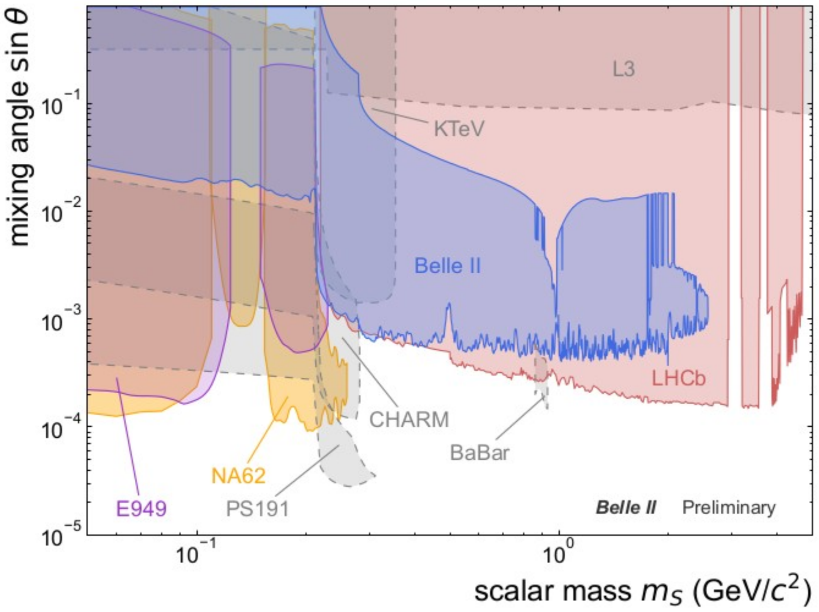


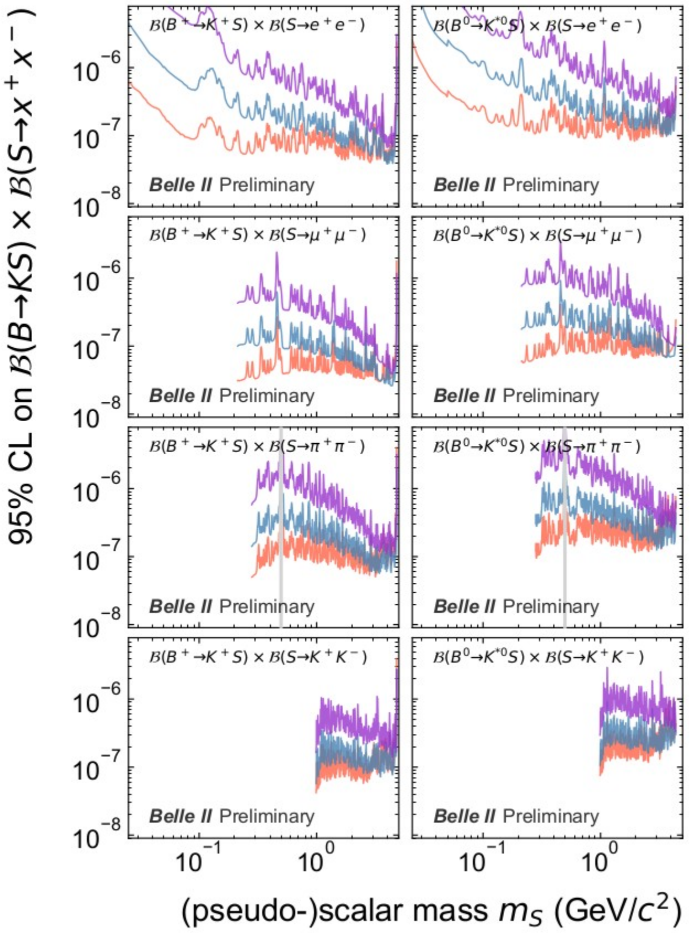


First model independent results for LLP

- 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]

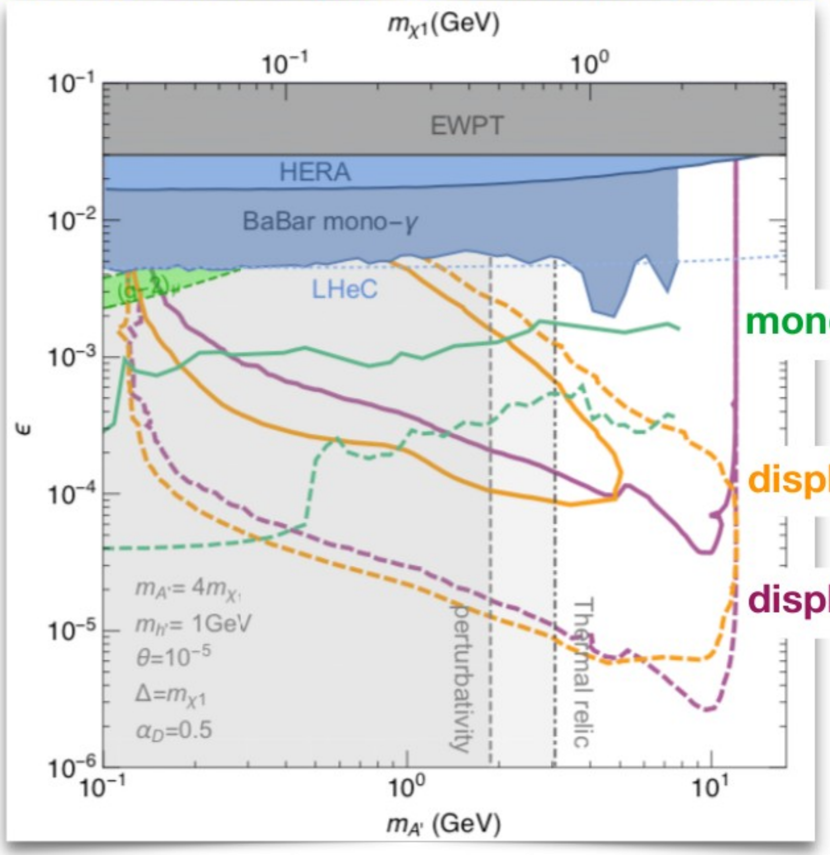




[1]: Phys. Rev. D 101 095006 (2020)

Belle II reach in IDM searches

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



100/fb

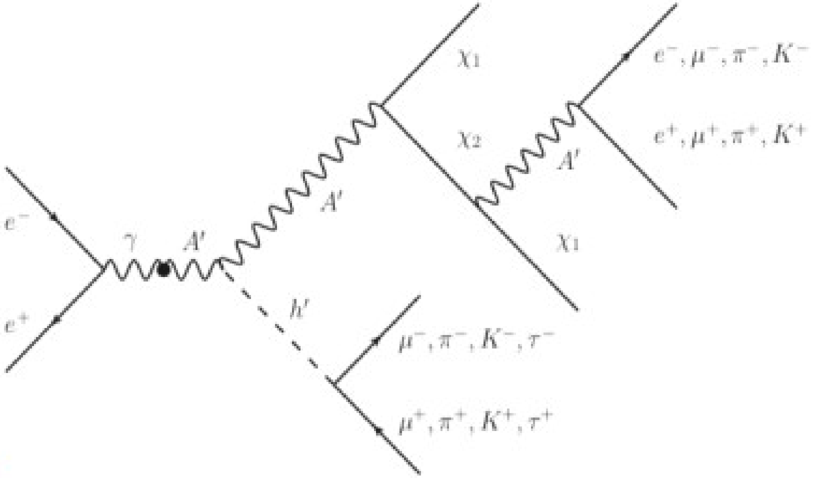
50/ab

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' ($\rightarrow$ SM SM) production

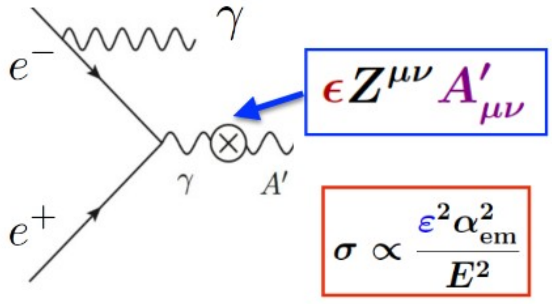
Displaced vertex trigger
is very important to obtain a good reach!

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

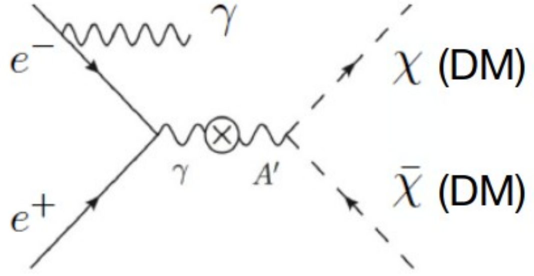
Invisible signatures

Example scenario: invisible dark photon

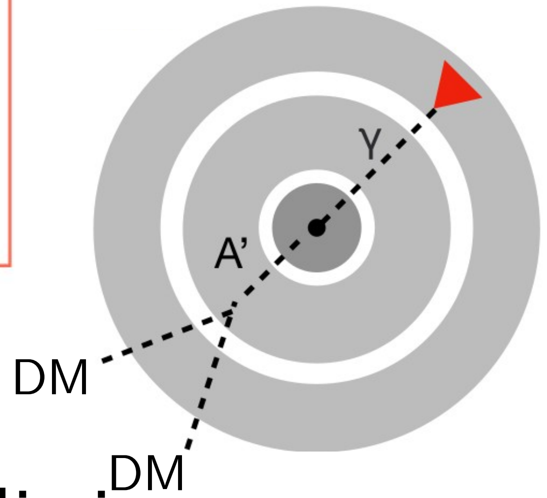
Production of a dark photon at B-factories:



Decay of the dark photon:



photon + invisible

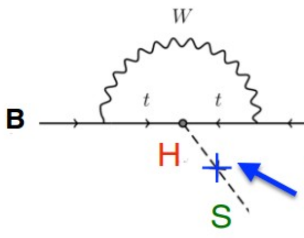


Missing energy

Visible signatures

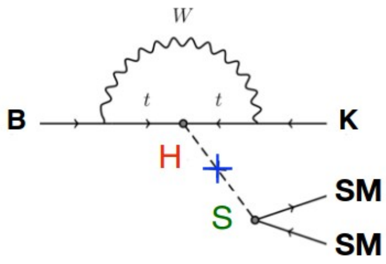
Example scenario: visible dark scalar

Production of a dark scalar at B-factories:

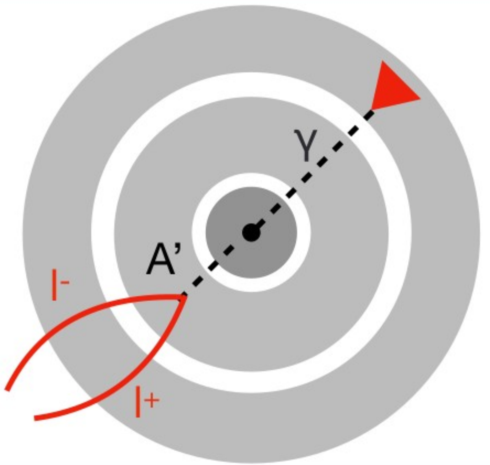


$\kappa|H|^2|S|^2$

Decay of the dark scalar:

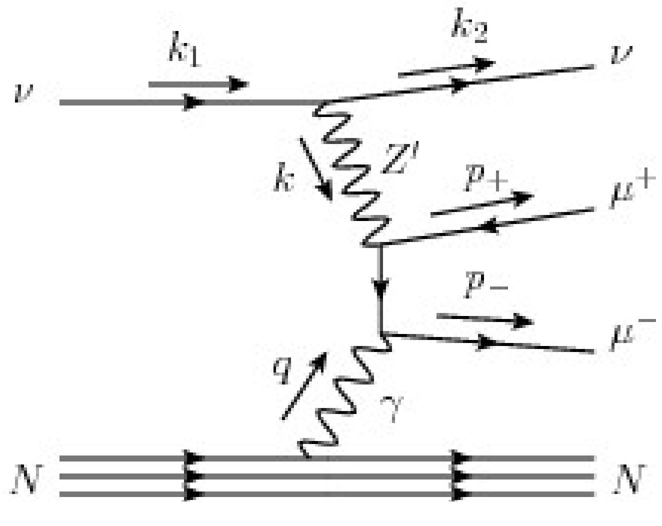


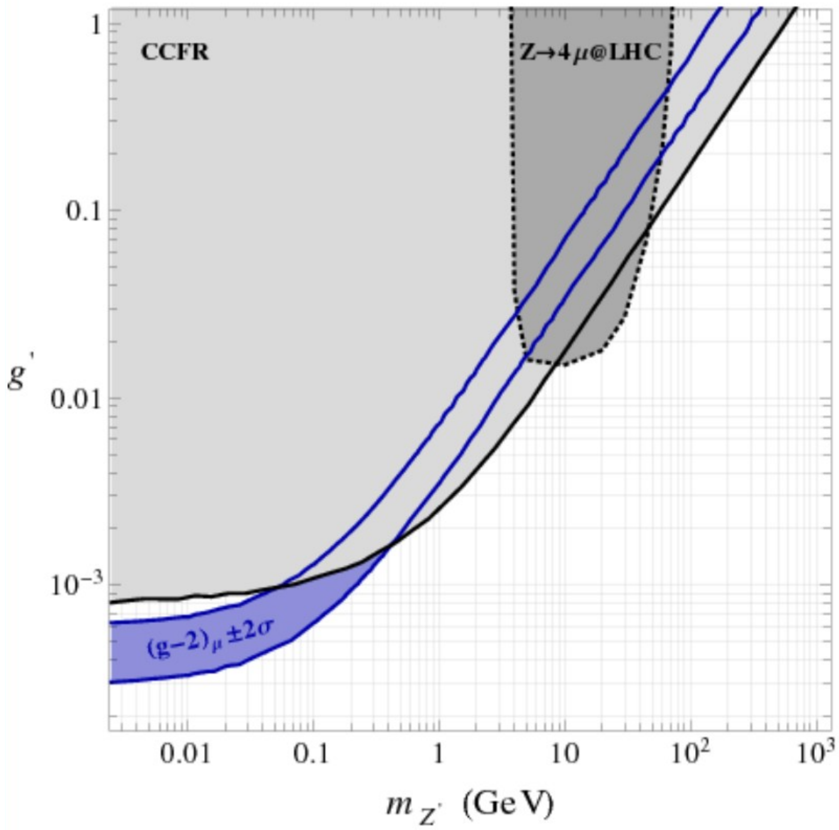
B→KS→Kμμ



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)