Long-lived particles at future collider experiments - focus on dark photons -

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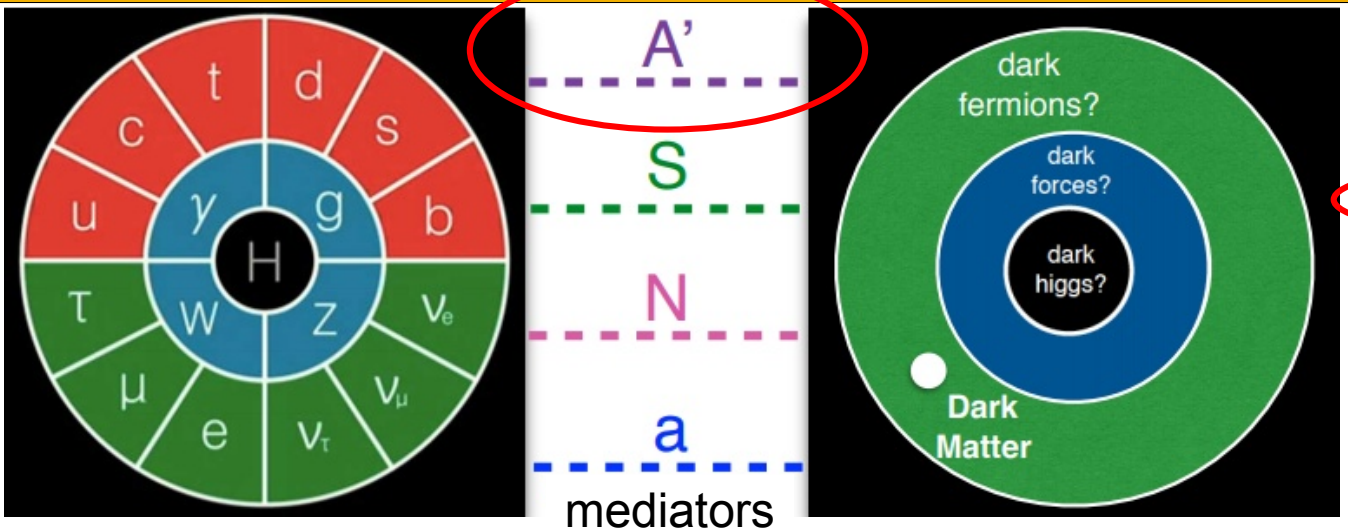
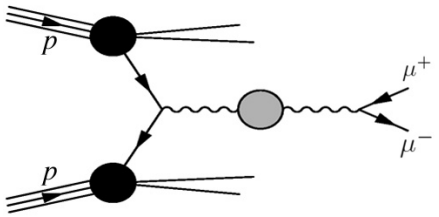
1st seminar in S-LLP,
Feb 25th, 2021

Dark/Hidden sector

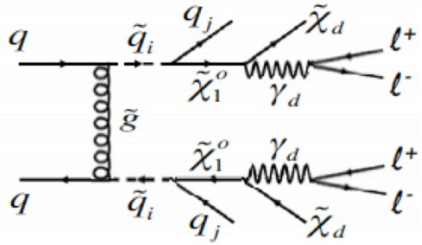


Mediator	Interactions
Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$yHLN$
Axion	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

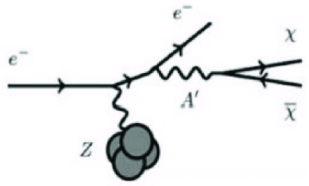
- A dark sector loosely connected with the SM can explain a large variety of unanswered question in particle physics (DM as a primary example)
- The mediator is only the portal to a (most likely) rich sector of new particles that, depending on its composition and mass spectrum, can give rise to simple or very complex signatures, still being explored



Visible A' decay to muons



Cascade dark-sector decay

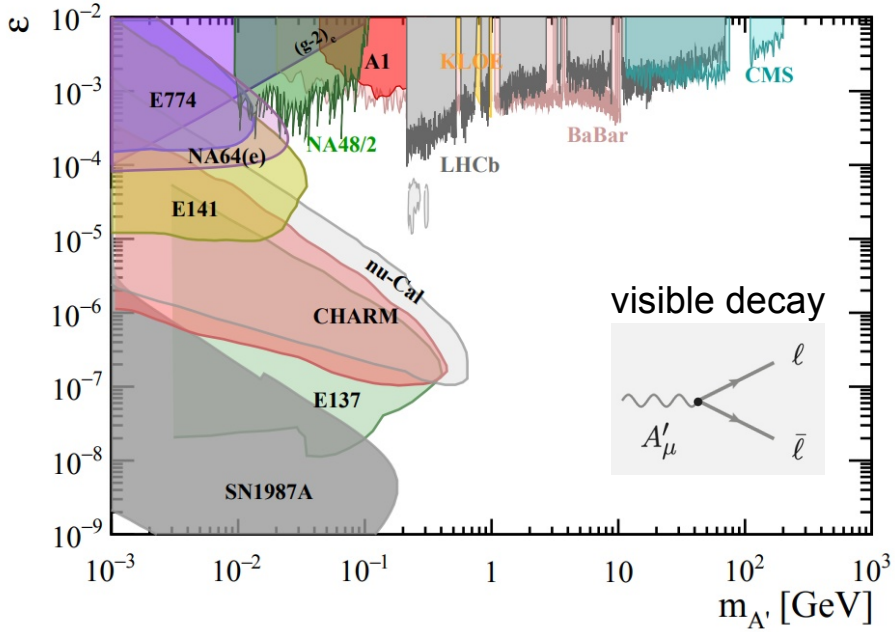


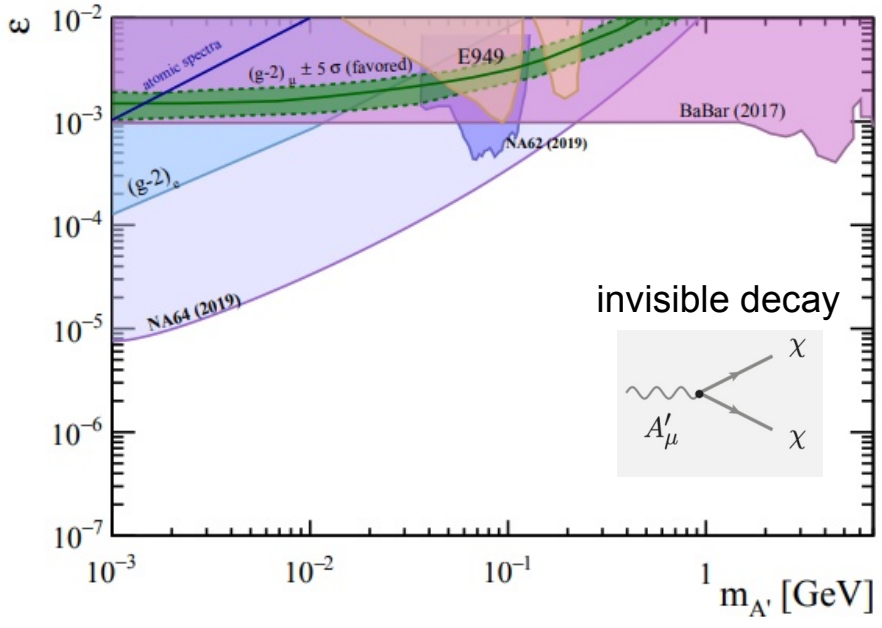
Invisible A' decay

… and much more

Experimental landscape

- Already a rich set of experiments probing different parameters space
  - Small couplings imply typically long lifetimes → long-lived particle signatures
  - For $m_{A'} < 1$ MeV → invisible decay, strongest constraints from cosmology





ε = dark-photon (A') to photon (γ) coupling

$m_{A'}$ = dark-photon mass

- For a recent full review, see e.g. arXiv:2005.01515

Outline

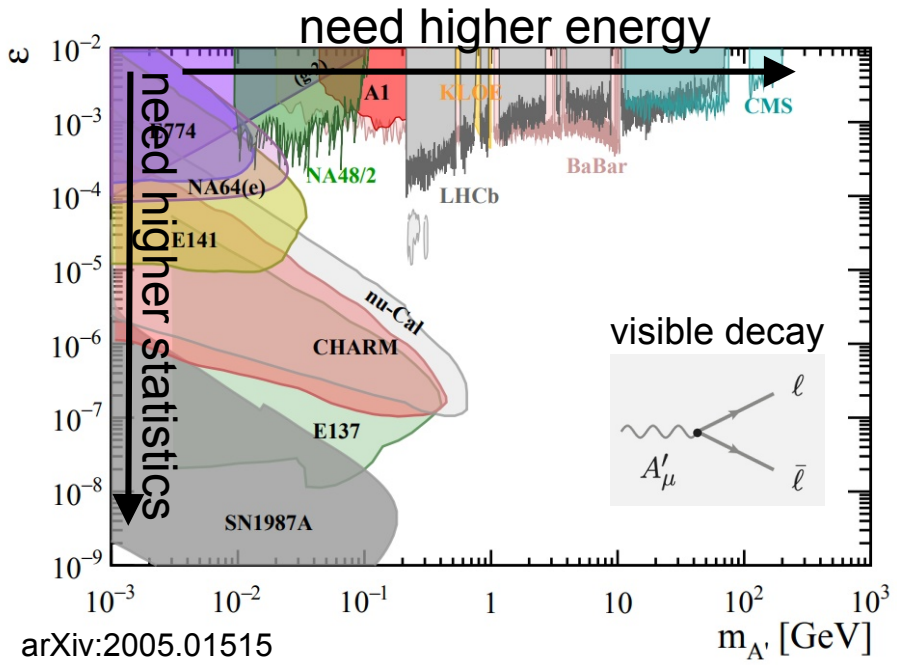
The focus of this talk is to give a glimpse into the vibrant ideas and projects that are been proposed or planned in the near (and distant) future

- Focus on experimental aspects, won't try to be comprehensive on model coverage nor give a detailed analysis of "gaps"
- Focus on experiments @ colliders

- Quick overview of classes of existing constraints
- Introduction to the Snowmass planning exercise
- Projects for HL-LHC
  - On-detector capabilities
  - External detectors
- Prospects for future colliders

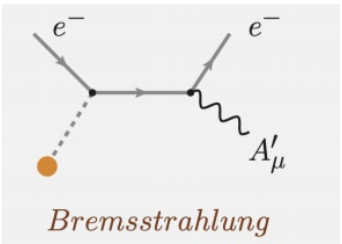
Experimental techniques

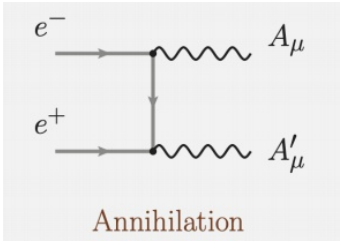
- Interplay between beam-dump and collider experiments

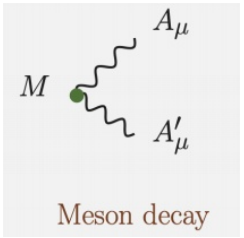


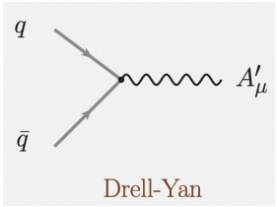
arXiv:2005.01515

production modes



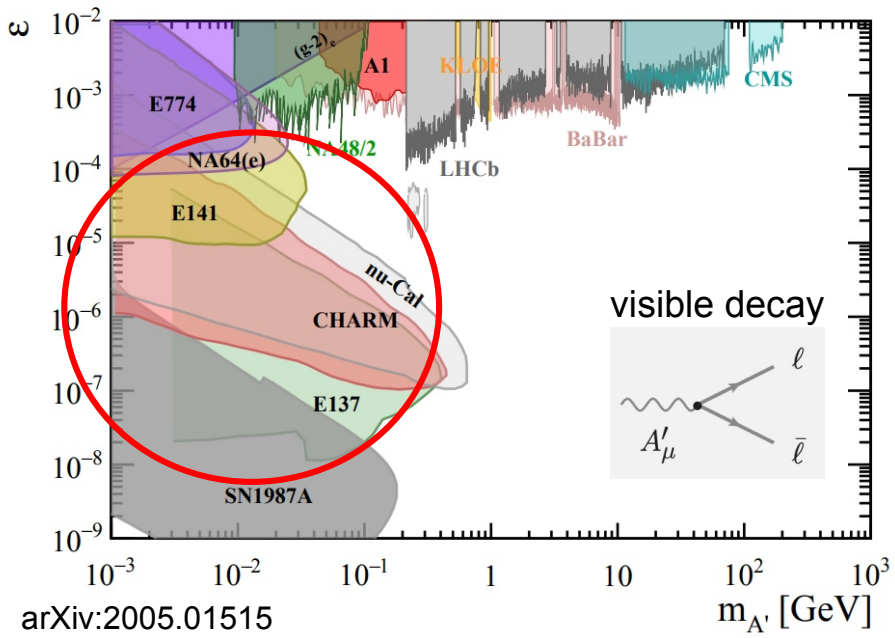






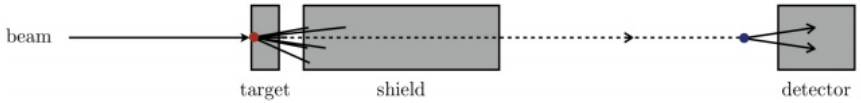
Experimental techniques

- Interplay between beam-dump and collider experiments



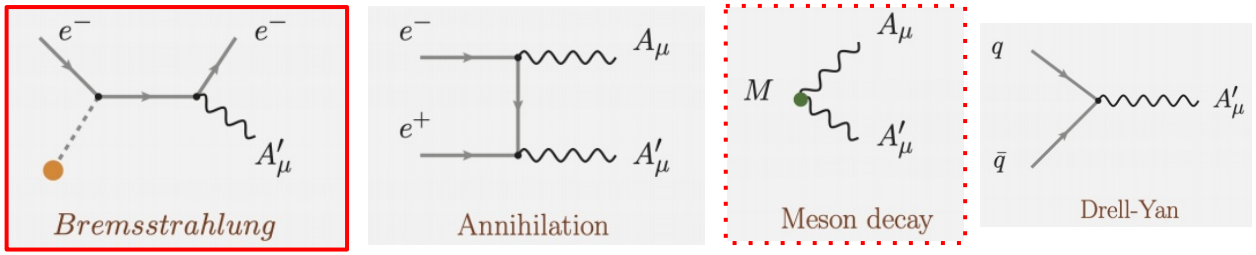
arXiv:2005.01515

Realm of beam-dump experiment



- High intensity electron and proton beams (SLAC, Fermilab, CERN)

production modes



Experimental techniques

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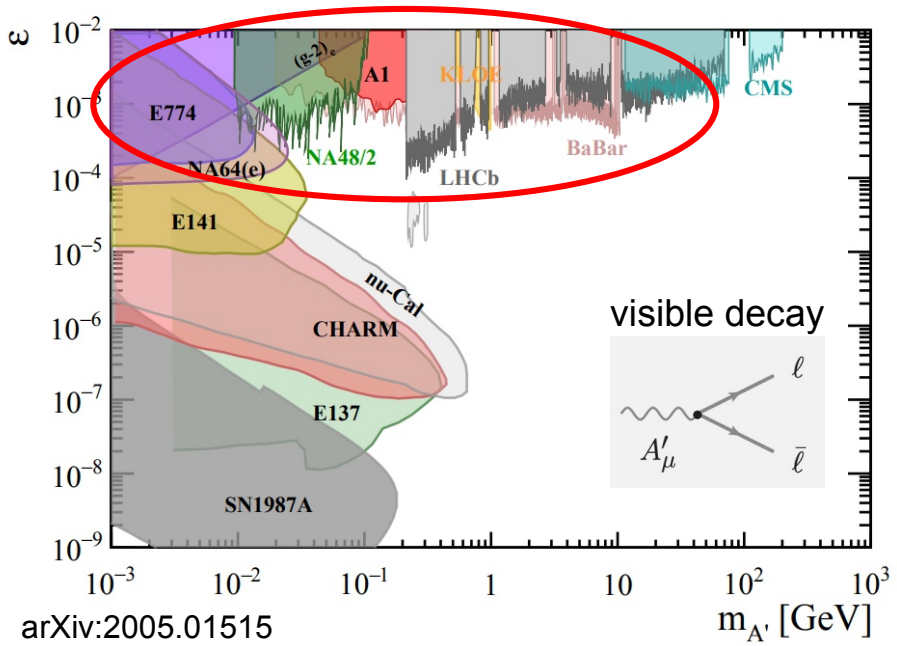

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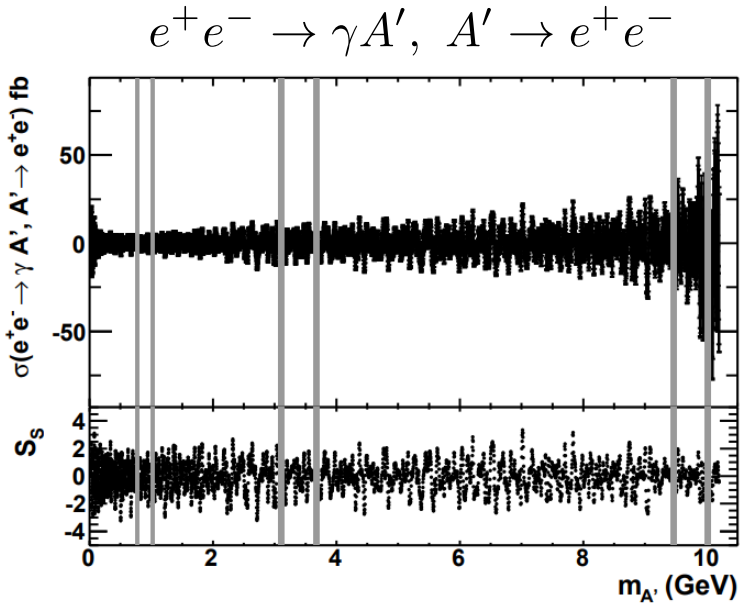
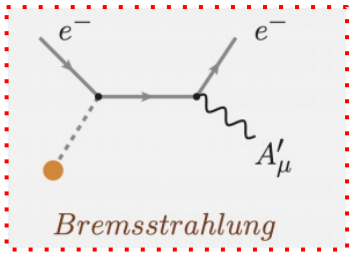
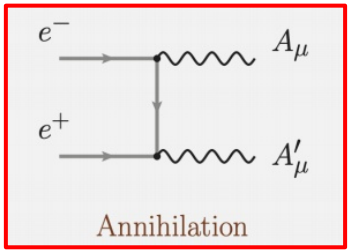
Region mostly dominated by meson decays and annihilation

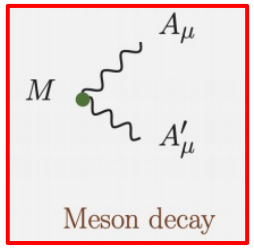


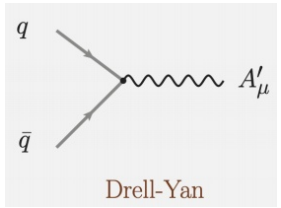
BaBar,PRL 113, 201801 (2014)

production modes



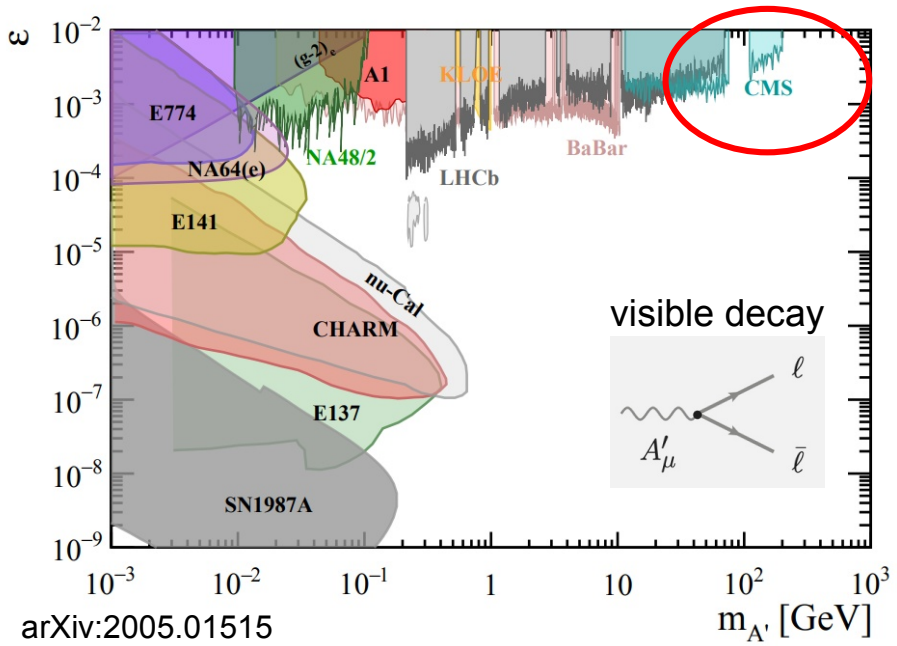






Experimental techniques

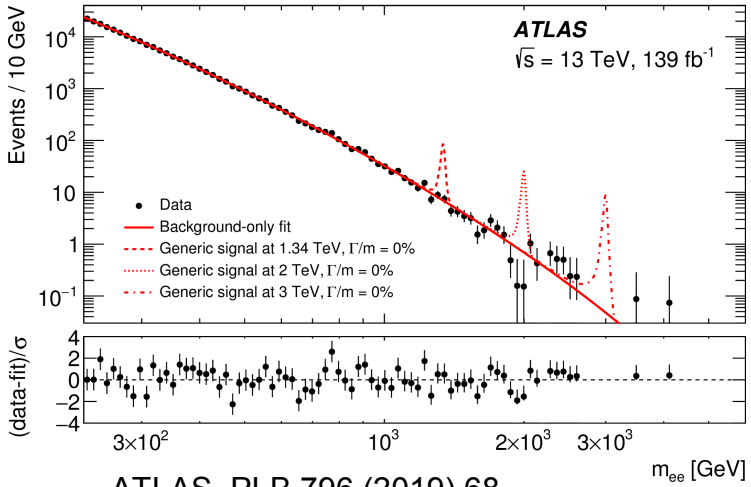
- Interplay between beam-dump and collider experiments



arXiv:2005.01515

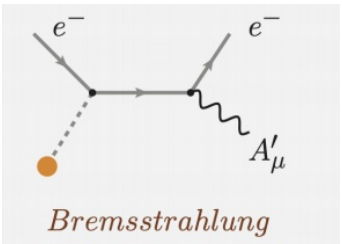
Realm of high-energy accelerators

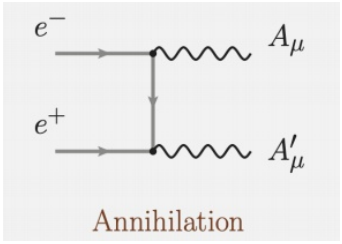
- Drell-Yan production dominates → searches for new resonances
- Prompt decay!

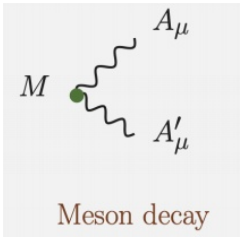


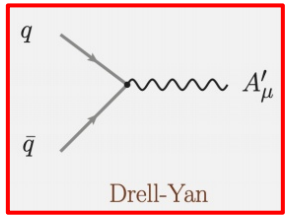
ATLAS, PLB 796 (2019) 68

production modes



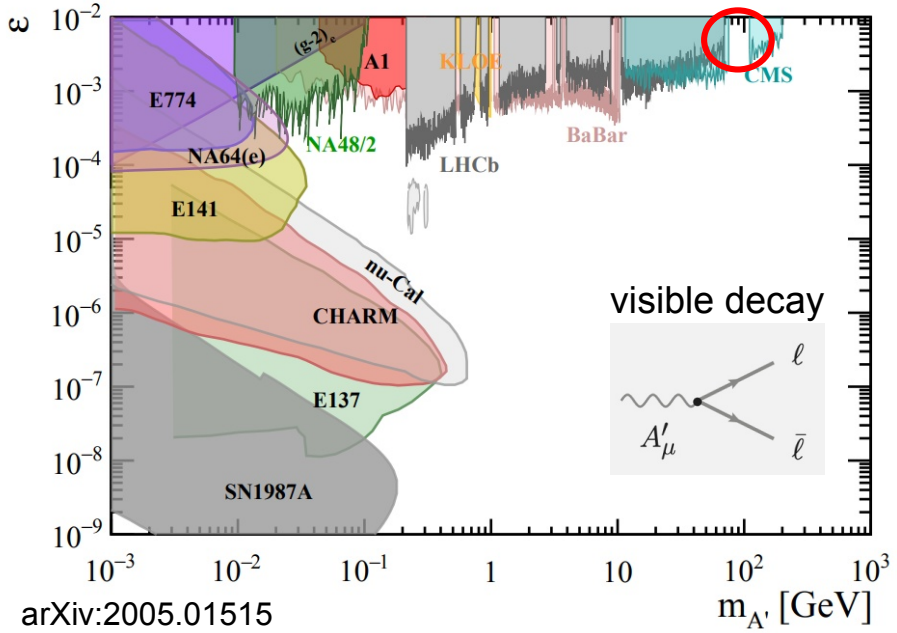






Experimental techniques

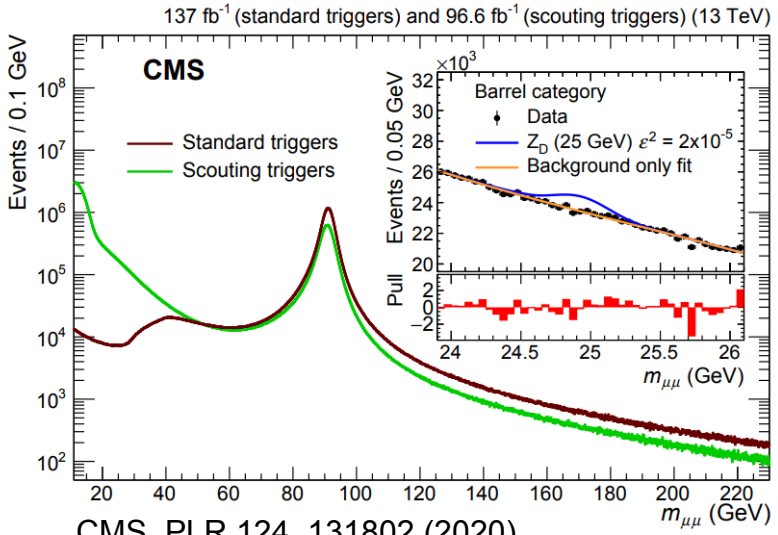
- Interplay between beam-dump and collider experiments



arXiv:2005.01515

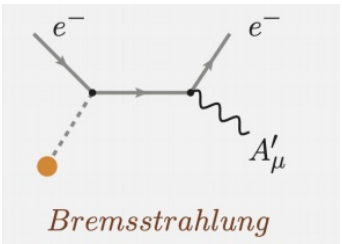
Realm of high-energy accelerators

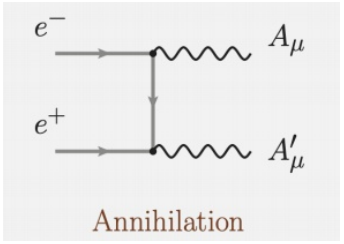
- And clever high-rate triggering with reduced event information

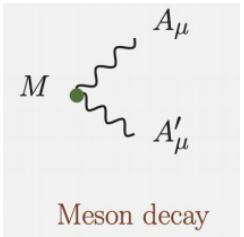


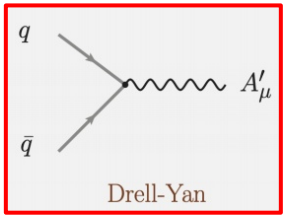
CMS, PLR 124, 131802 (2020)

production modes



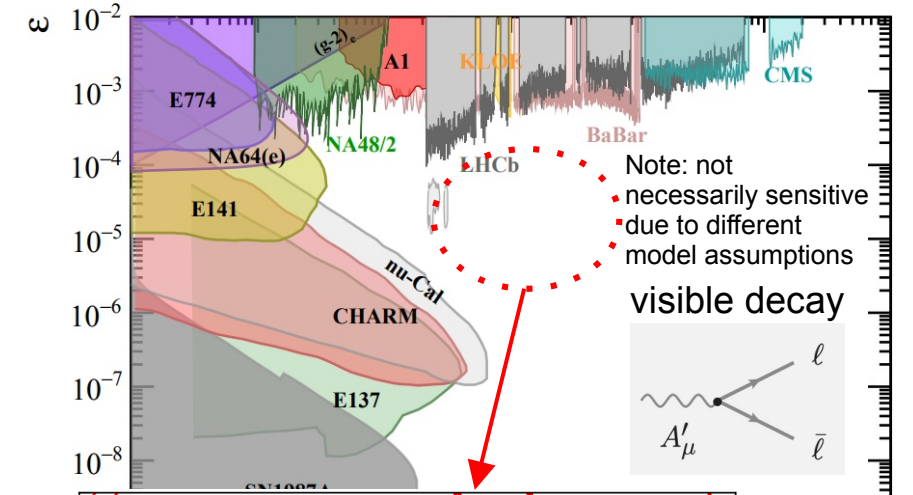


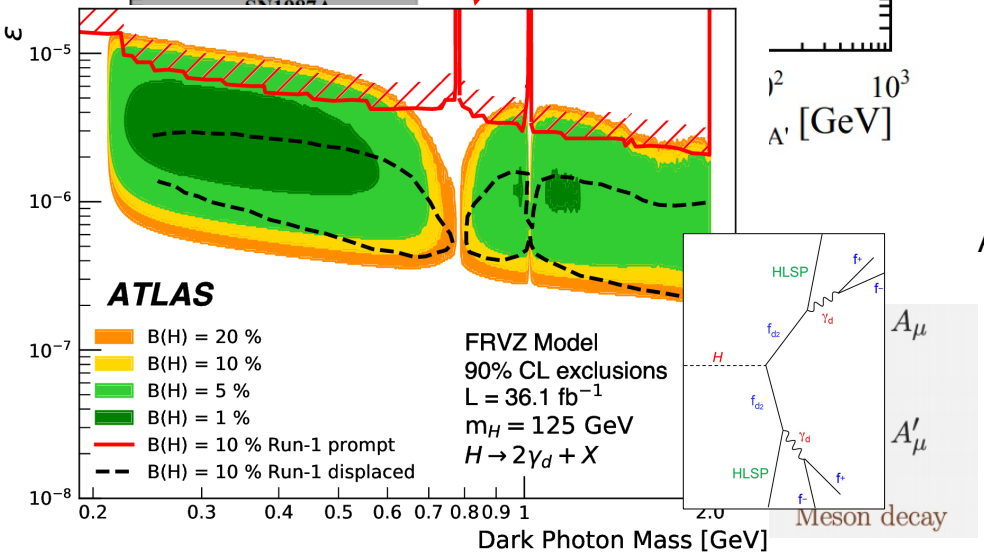


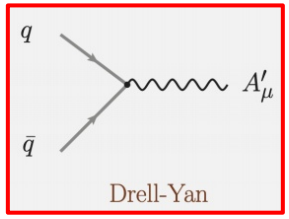


Experimental techniques

- Interplay between beam-dump and collider experiments

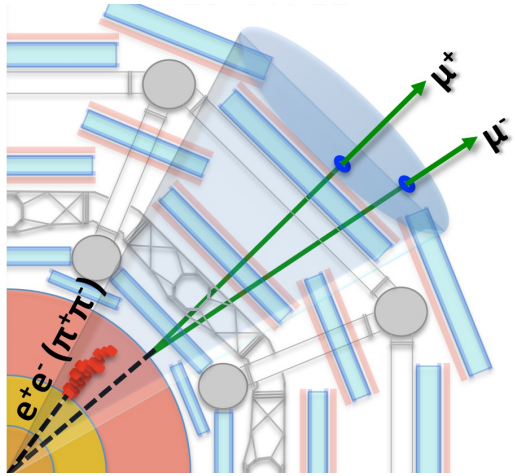






Realm of high-energy accelerators

- Displaced decays in the inner tracker, calorimeter and muon spectrometer

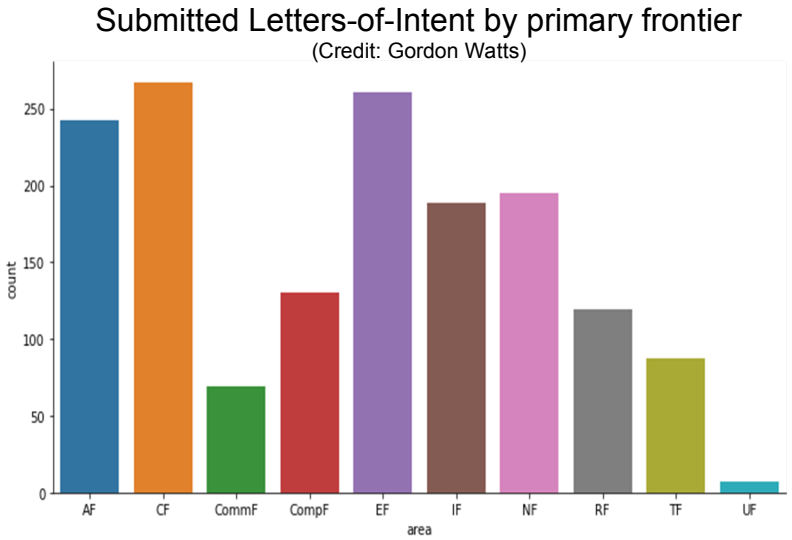


ATLAS, e.g. JHEP11(2014)088, Eur. Phys. J. C 80 (2020) 450

Planning future strategies

- Currently ongoing “Snowmass” process in the US [https://snowmass21.org/]
  - Defined as a science study group, aims to identify a vision for the future of particle physics in the U.S. and its international partners
  - Analogous to the recent European Strategy planning [REPORT]
- Snowmass is currently in “slow-down/pause” mode until the summer and aims for a final report in the fall of 2022 (detailed reports to come earlier)

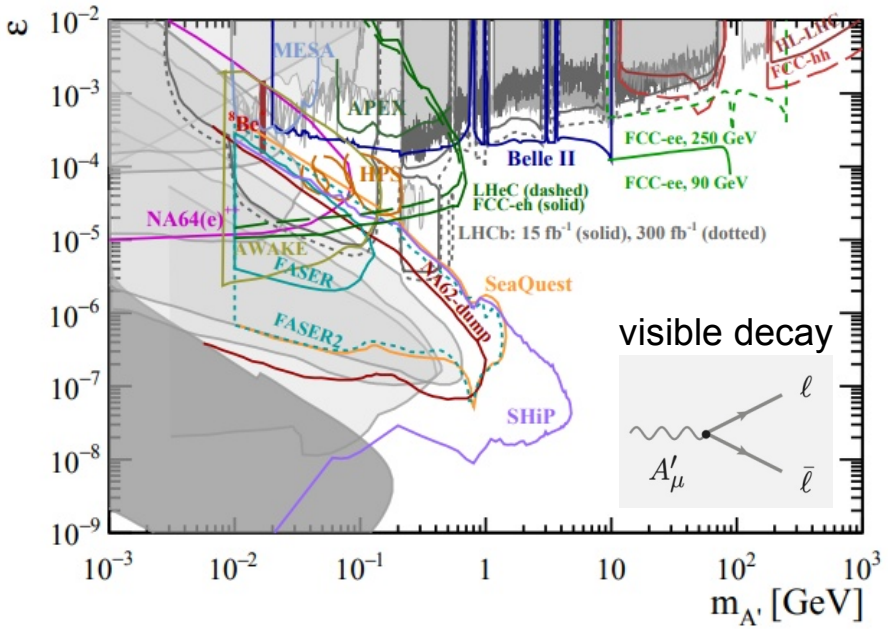
Snowmass Frontiers
Energy Frontier
Neutrino Physics Frontier
Rare Processes and Precision
Cosmic Frontier
Theory Frontier
Accelerator Frontier
Instrumentation Frontier
Computational Frontier
Underground Facilities
Community Engagement Frontier

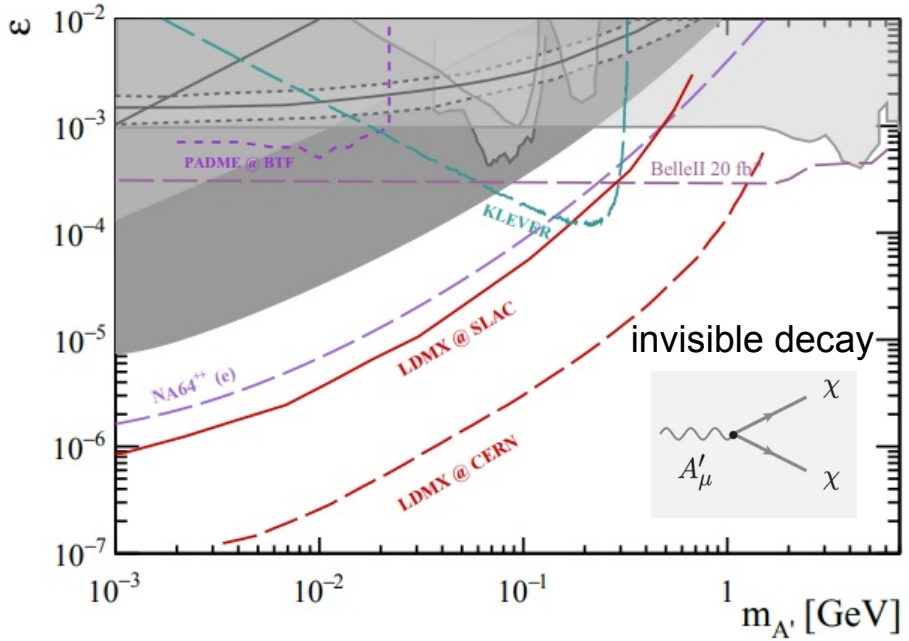


(Near) future of beam-dump experiments

- Building on the work of other dedicated study groups as Physics-Beyond-Collider and the US Basic-Research-Needs study
- Primarily discussed within the Rare Processes and Precision frontier

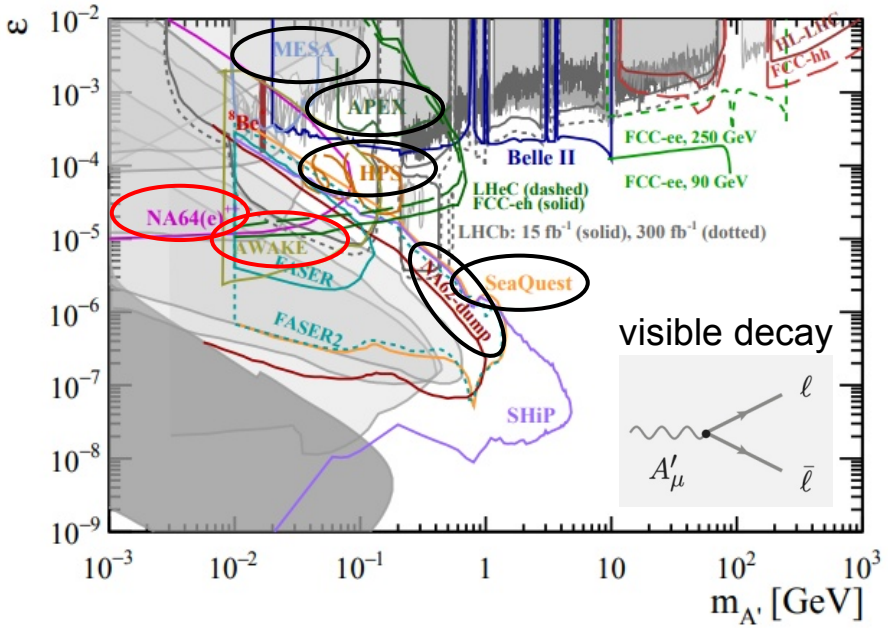
More info on e.g. S. Gori's talk at Snowmass CPM [LINK]

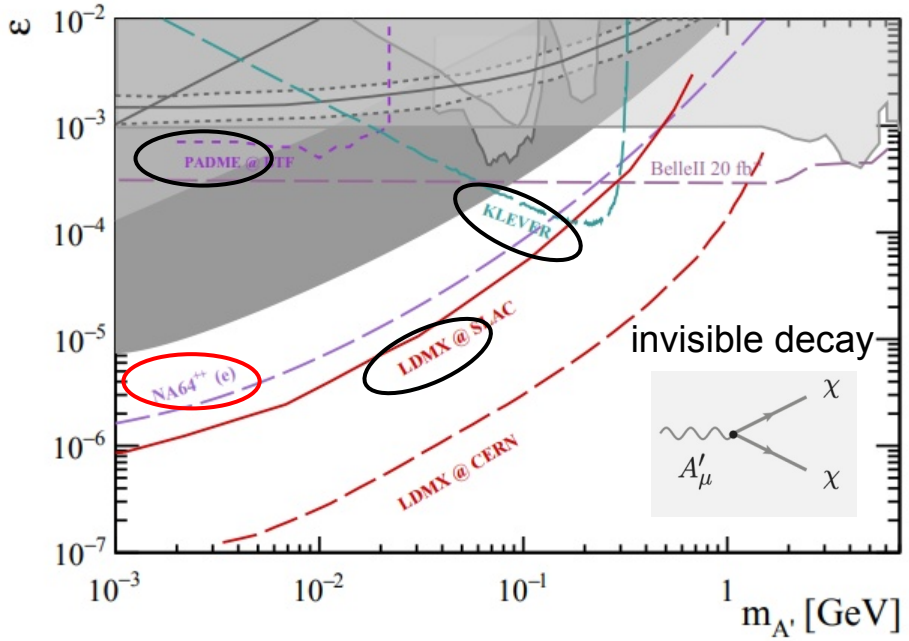




- Several new or upgraded experiments proposed and many are expected to take data within the next decade

(Near) future of beam-dump experiments

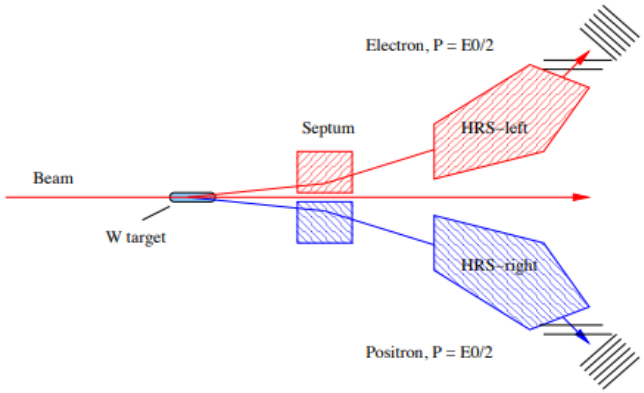




NA64^{++}, APEX
electrons on target
Will run in the next few years

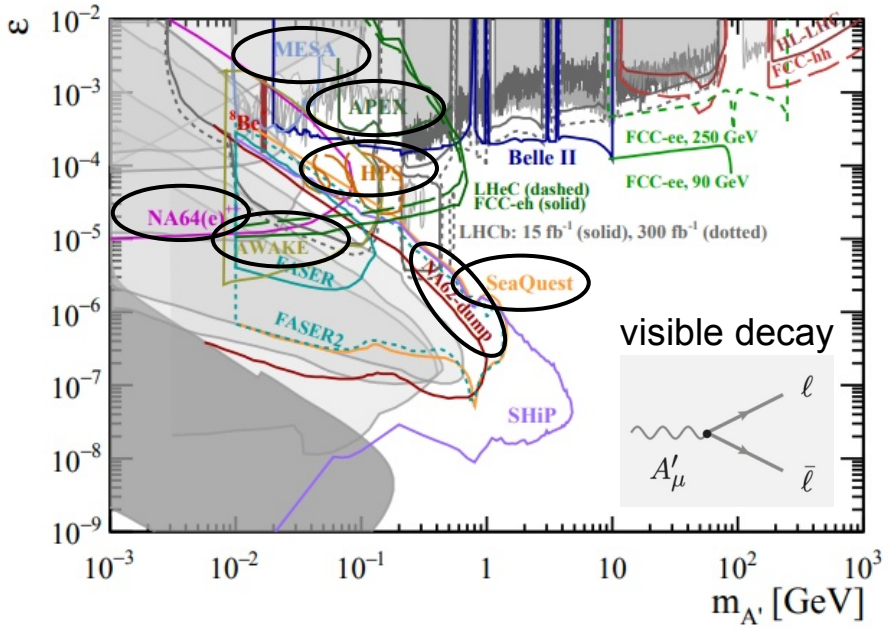
NA62^{++}
protons on target @ CERN

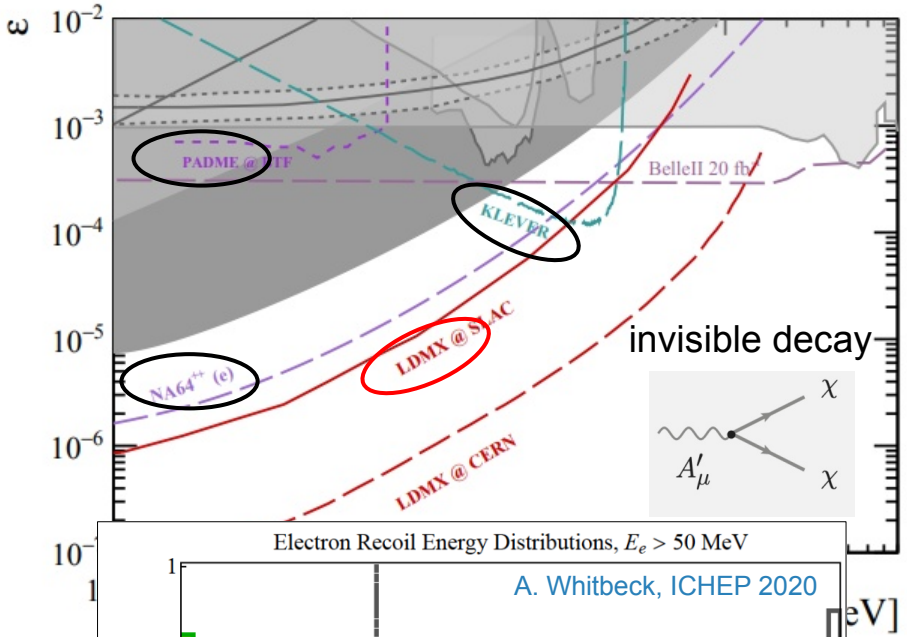
AWAKE
Using plasma-wave acceleration
to collide electrons on target

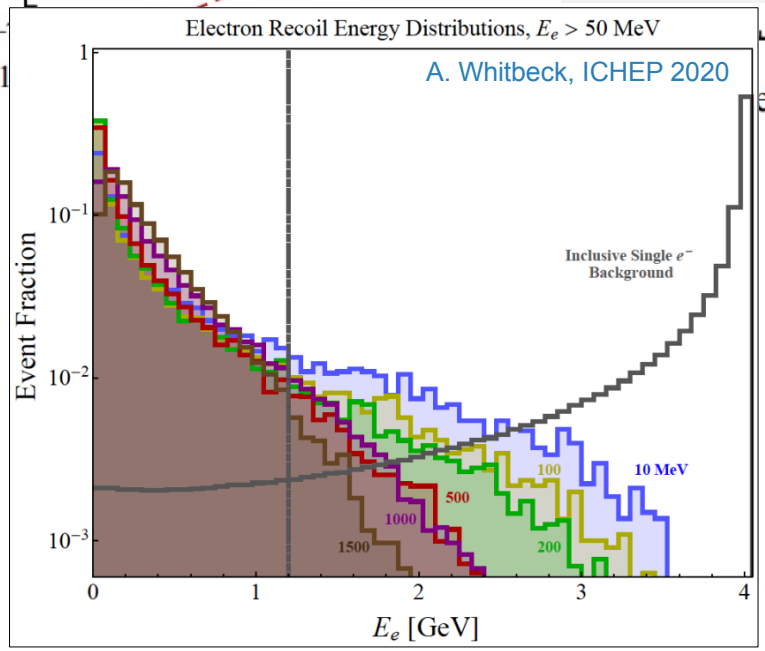


Reconstruct dark photon mass

(Near) future of beam-dump experiments

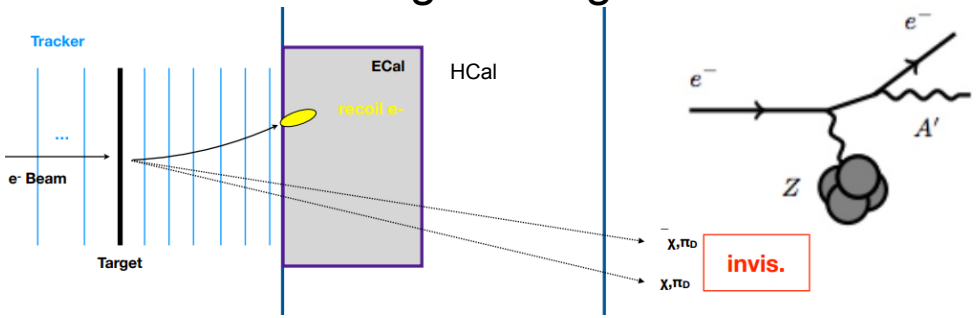






LDMX

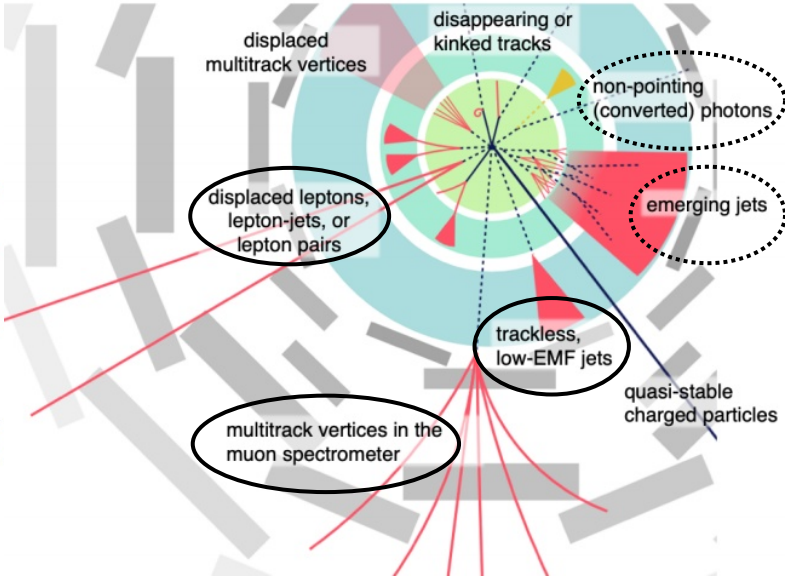
Based on detecting missing A'



... and several more ideas being explored!

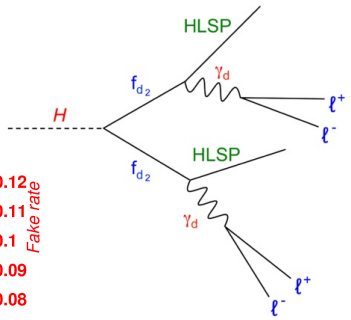
High-Luminosity LHC

- HL-LHC is a baseline reference for collider physics
  - Equally important the continued support to maximize its scientific output
  - Further upgrades for/during HL-LHC can enhance its reach
- Rich set of signatures explored at the ATLAS/CMS/LHCb experiments
  - Many of which sensitive to dark photons



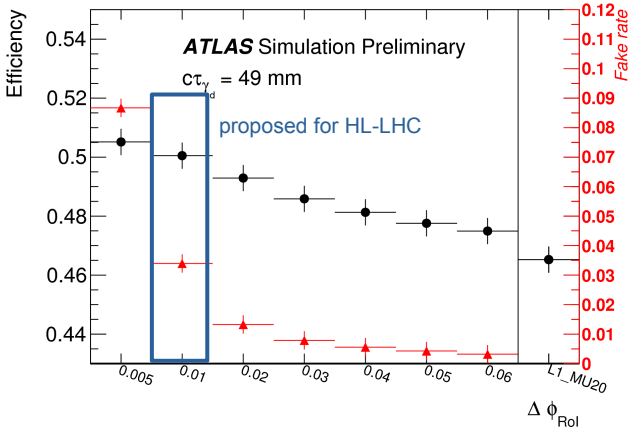
Displaced lepton-jets

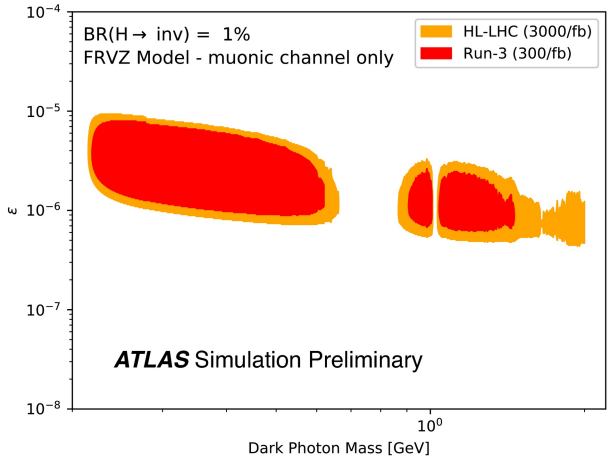
- Search for dark photon decays to leptons in the tracker, calorimeter or muons spectrometer (MS)
  - Typical model: Higgs-portal with multiple dark-photon decays



Muon Spectrometer

- Dedicated triggers!
- Upgrade of MS for ATLAS/CMS yields improved sensitivity
- Careful developments to address LLP-specific inefficiencies:
  - Collimated decays
  - Sagitta measurement bias
- Achieves much improved sensitivity probing Higgs branching ratios much below 1%

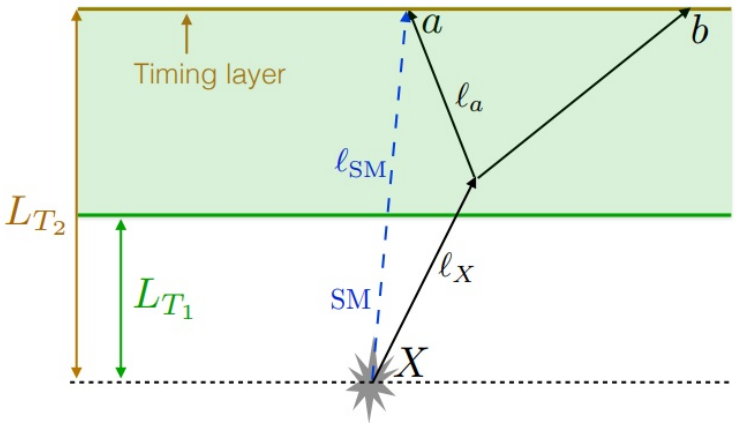




(aside:) Timing and Calorimeters

Dedicated Timing detectors

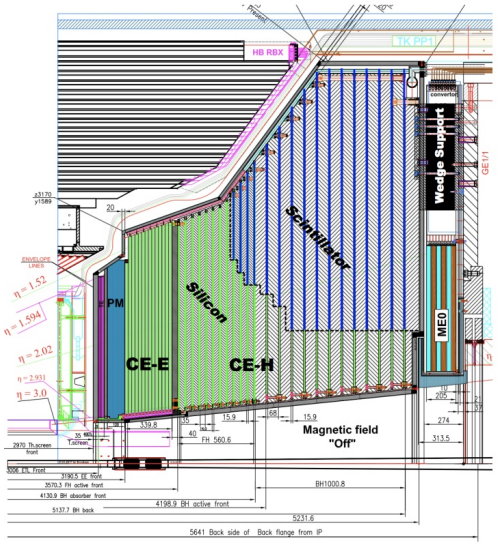
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$



- CMS (central) and ATLAS (forward) will install dedicated timing layers with ~30 ps time resolution
- Mostly target heavy states with β << 1
  - Also sensitivity from longer flight-paths

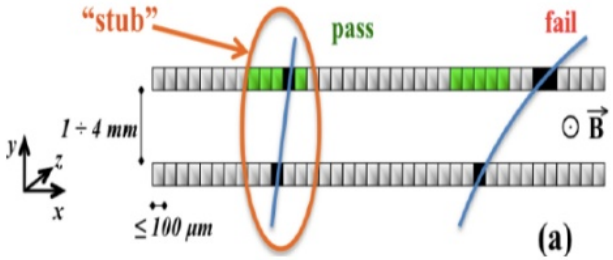
Calorimeters

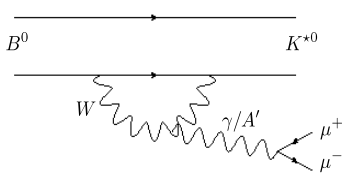
- CMS to install a high-granularity Silicon imaging calorimeter
  - tracker + calorimeter + timing detector all in one!
  - Still exploring how the fine segmentation and timing information can benefit LLP searches, but plenty of potential

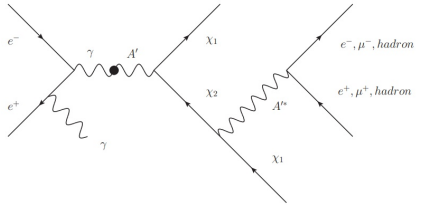


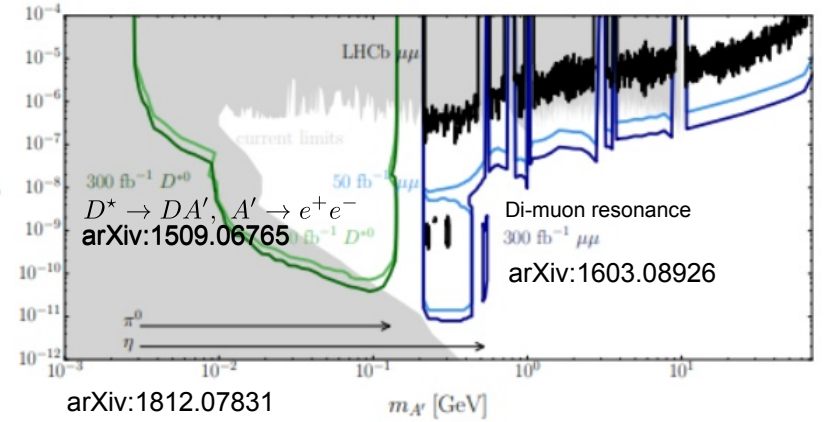
Inner tracker

- Target mid-low mass dark photons
- Triggering on inner tracker activity often a major limitation of LLP searches
- LHCb “high-luminosity” phase soon
  - real-time processing of event with ~ no trigger (30 MHz) and quasi-offline quality
  - Sensitive to O(1-10cm) displaced decays
  - Alsso expect results from e.g. BelleII, BESIII
- CMS track-based level-1 triggers
  - “double” silicon layers of tracking detectors
  - Direct triggering on displaced di-μ decays



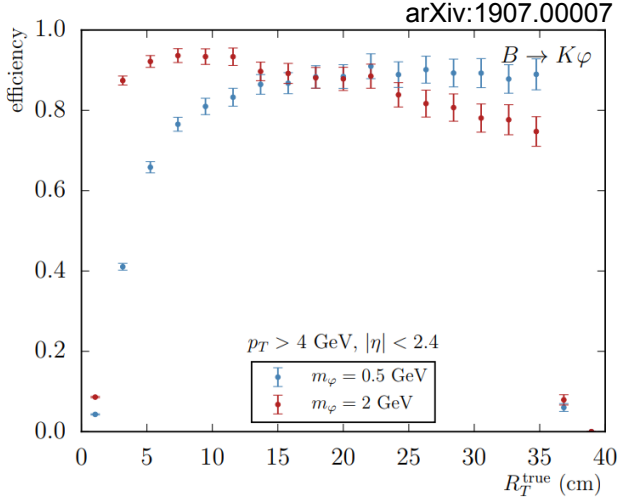






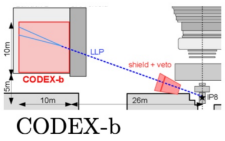
arXiv:1812.07831

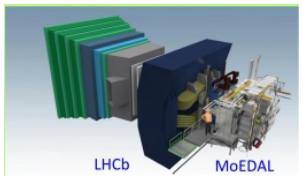
arXiv:1907.00007

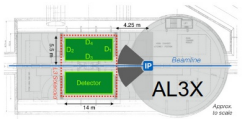


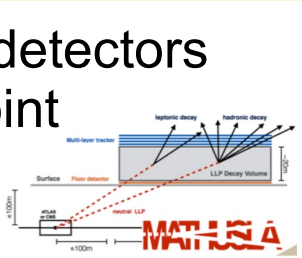
External detectors at HL-LHC

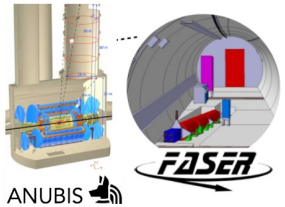
- Complement sensitivity with external detectors for LLP produced at the interaction point
  - Several proposals at different stages, all aimed at the LHC/HL-LHC

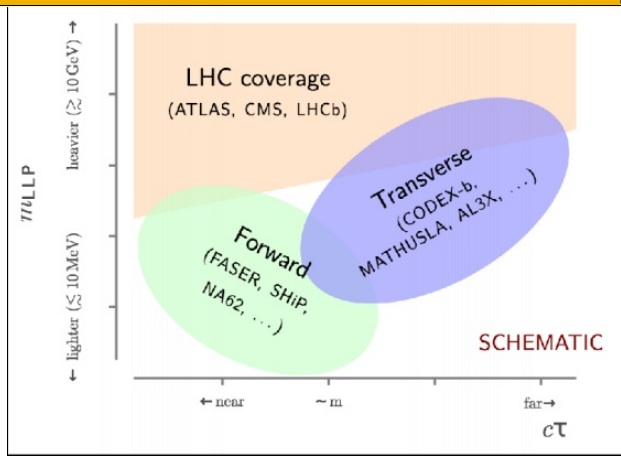


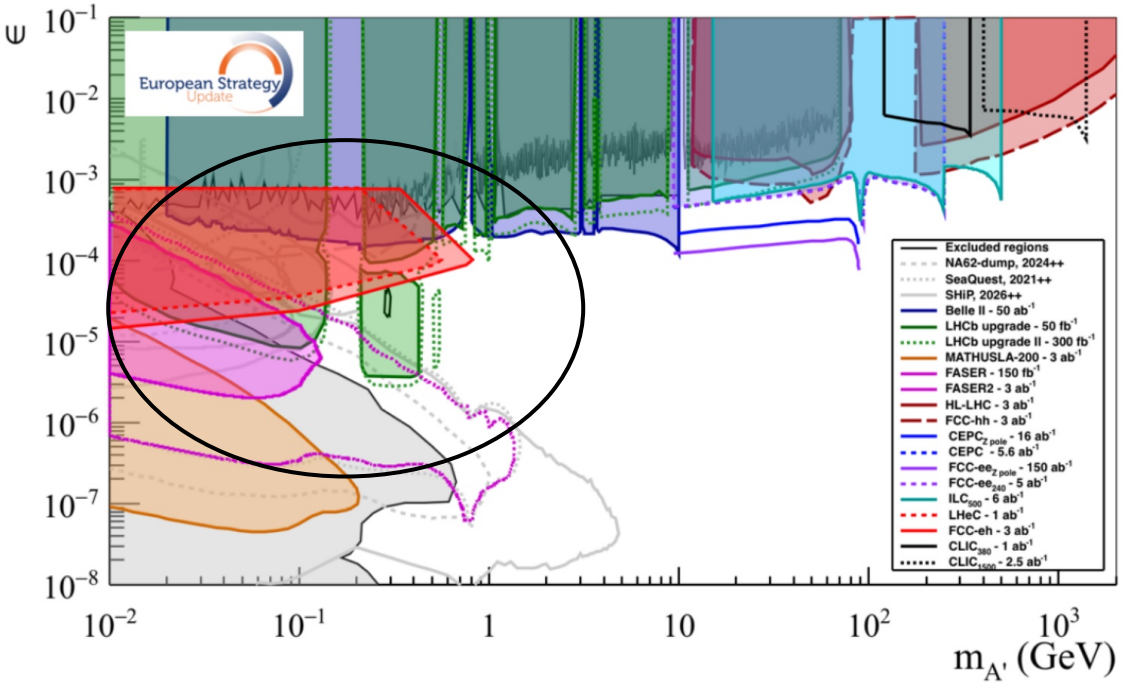












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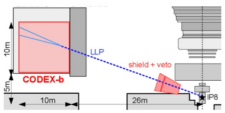
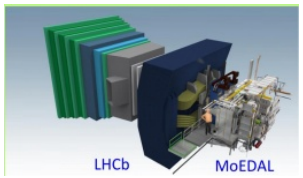
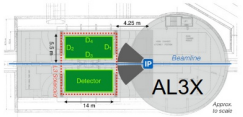
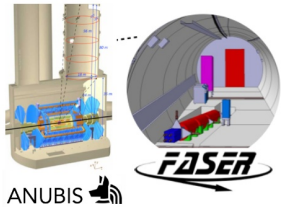
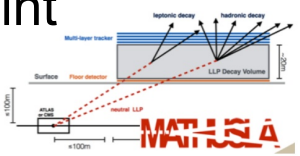
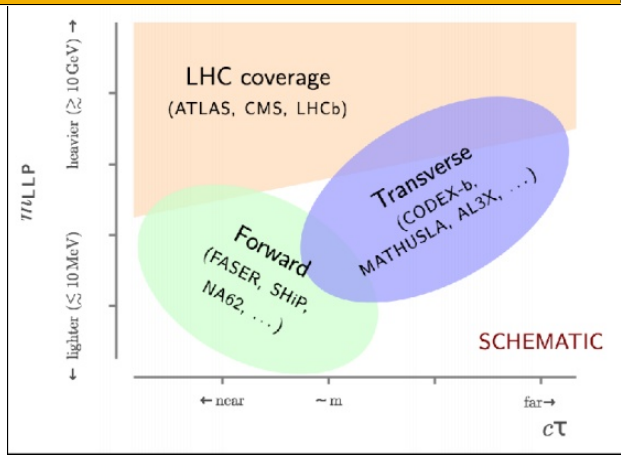




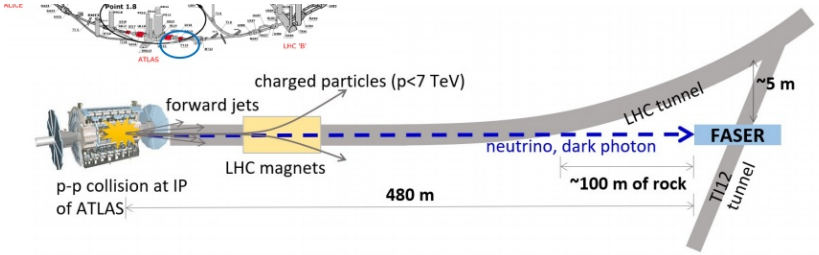


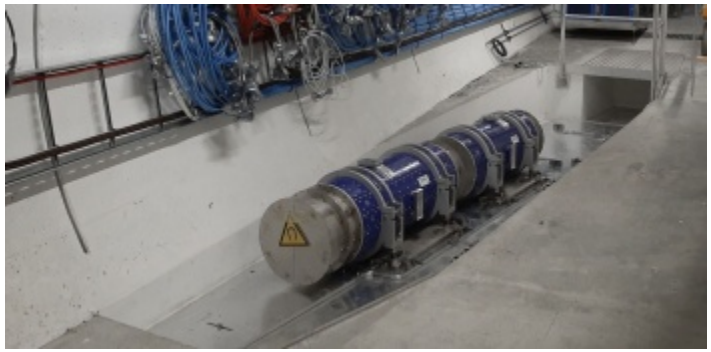






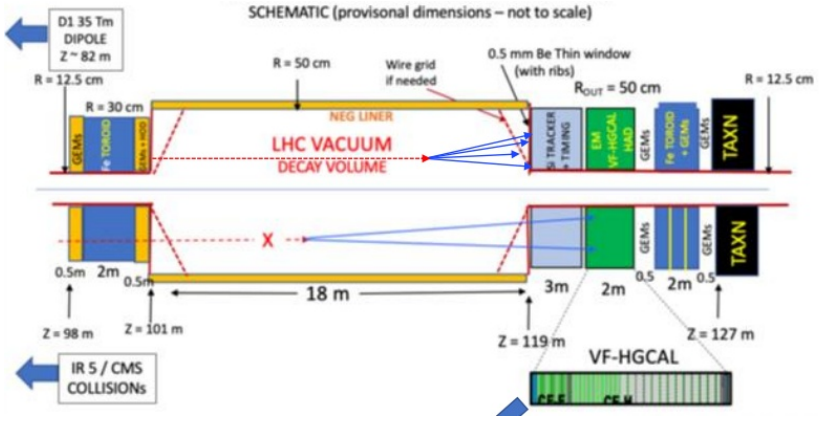
FASER (now!)





CMS Forward Spectrometer

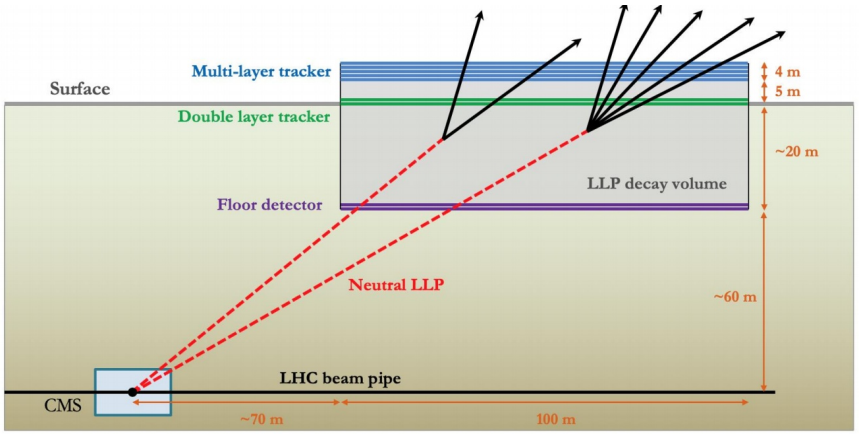
- New proposal, narrowly fitting in "empty" space in LHC setup



External detectors at HL-LHC

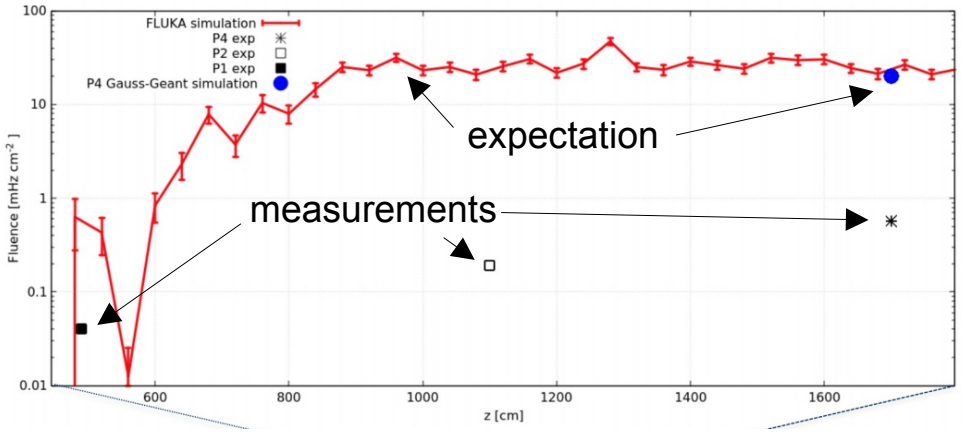
Mathusla e.g. arXiv:1811.00927,arXiv:2009.01693

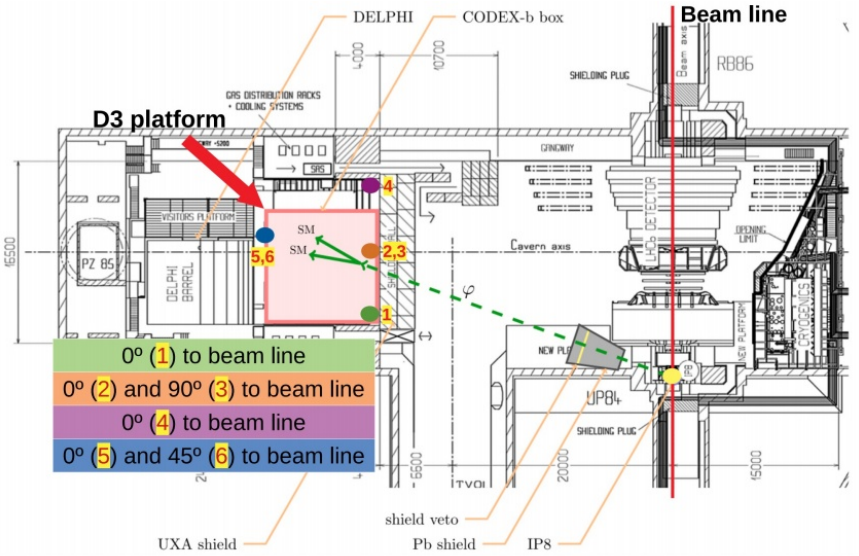
- Simulation and in-situ background estimate → expect < 1 bkg event / yr
- Associate with CMS recorded events
  - ideally incorporate in trigger



Codex-b e.g. arXiv:1911.00481,1912.03846

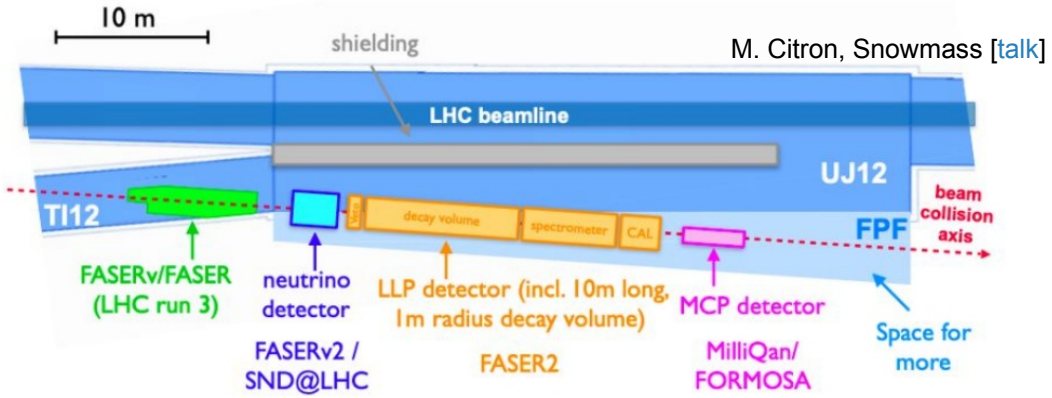
- Tested background assumptions with measurements in LHCb cavern
- Aim to build a demonstrator (Codex-β)





Forward physics facility

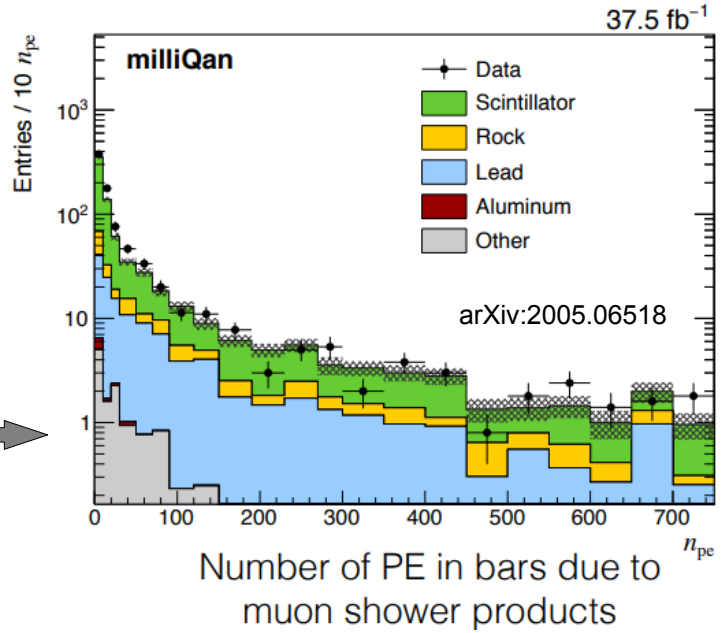
- Space always an issues for such “external” experiments
- Proposal to build a dedicated forward-physics facility cavern
- Supporting a suite of far-forward experiments
  - e.g. FASER2 and more..



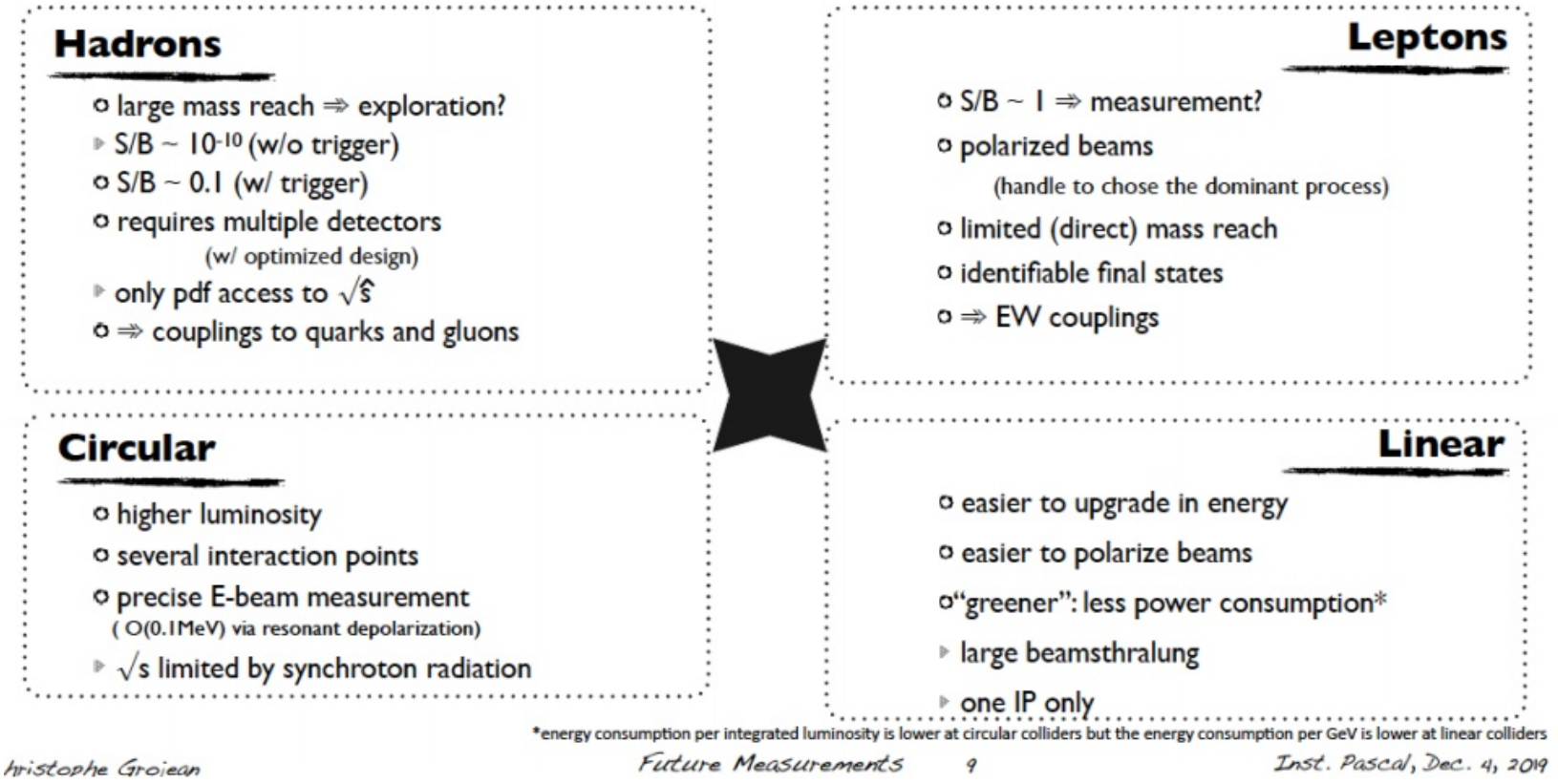
M. Citron, Snowmass [talk]

MilliQan/Fermini/Formosa [e.g. arXiv:1410.6816]

- Milli-charged particles
  - e.g. in massless dark-photon scenarios
- Signal amplified in several scintillators
  - Reduce backgrounds via multiple layers
- MilliQan demonstrator has taken data
- Location/setup produce complementary sensitivity in mass/coupling plane



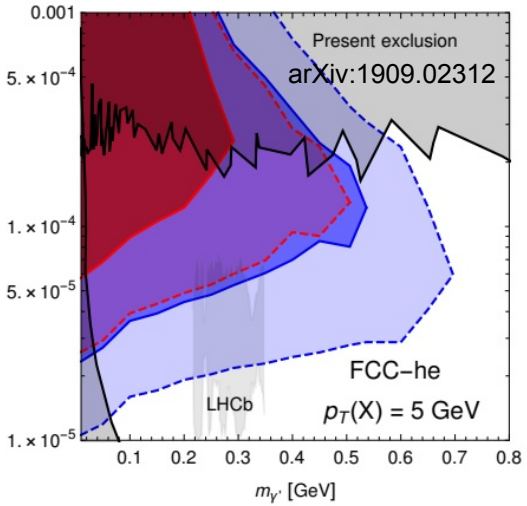
Future (high-energy) colliders

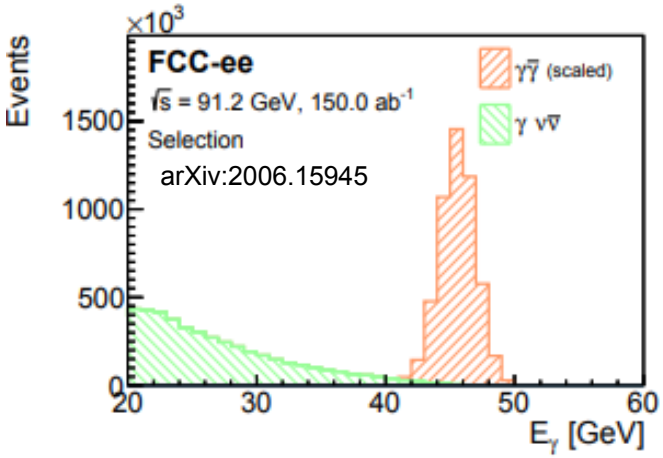


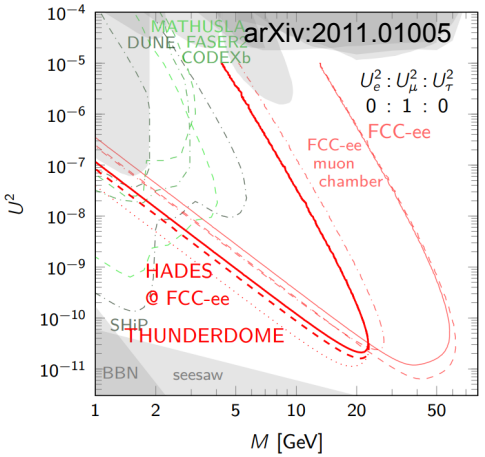
- Many options being considered after HL-LHC in the context of snowmass
  - Also including electron-hadron colliders, photon-photon colliders, etc..
- Vast physics program for each, and searches for long-lived particles are part of the physics program for such accelerator proposals

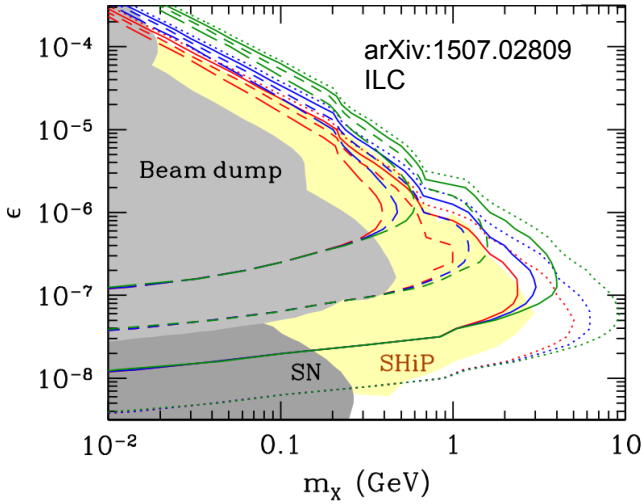
Dark photons at future colliders

- LLP reconstruction in future colliders' detectors is being studied
  - more projections expected in the context of snowmass (at least ~5 new results expected on dark-photons at future colliders)







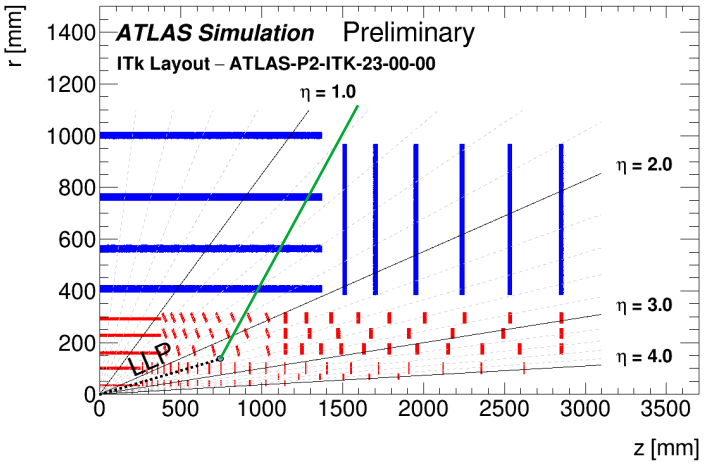


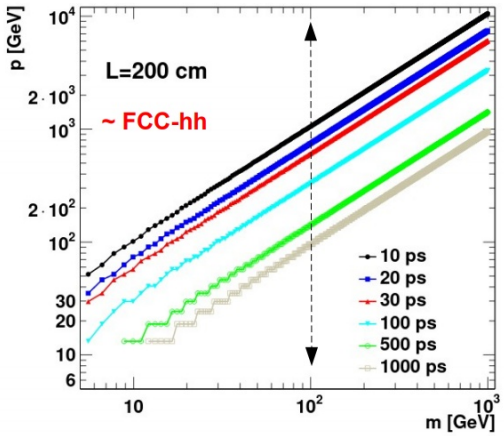
- New beam-dump opportunities e.g. at ILC
- New external detectors
  - General studies on best locations
  - Proposals for instrumenting the cavern (e.g. HADES)

Detector requirements

See e.g. Snowmass CPM dedicated session

- Open discussions on detector requirements for LLP detection
  - Hermeticity/Geometry
  - Readout and powering (beta << 1)
  - High granularity @ large radius
  - Particle ID (TOF, dE/dx, …. high-pT?)
  - Timing in ~every sub-detector
  - Trigger/data-flow/software flexibility
- Lack of collider-specific studies on most

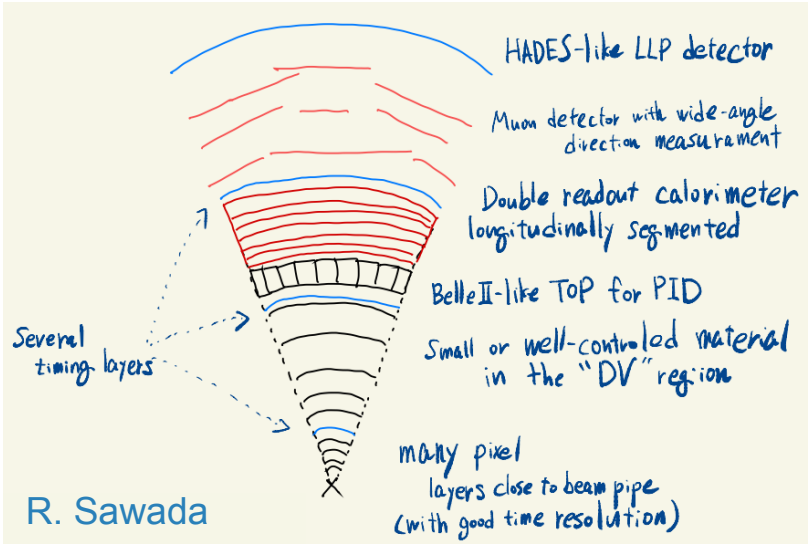




BSM particle with M=100 GeV can be identified up to momentum:
- 700 GeV in |p| for σ_{TOF}=20 ps
- 70 GeV in |p| for σ_{TOF}=1 ns

Can identify massive stable particles in very boosted regime!

Snowmass21 contributed paper: arXiv:2005.05221



Conclusions

- A dark/hidden sector can generate a wide variety of signature
- Interplay between various experimental techniques is vital to explore the possible parameters space
- A large variety of experiment are being carried out, and many more are being proposed to extend the sensitivity and cover gaps
- The Snowmass process provides a good platform for the international community to produce dedicated studies on LLPs (and dark photons, in particular) and harmonize their presentation
- Detector requirements for future colliders, specific to LLPs, should not be overlooked and can provide unique motivations for technology R&D

BACKUP

Interplay with European Strategy

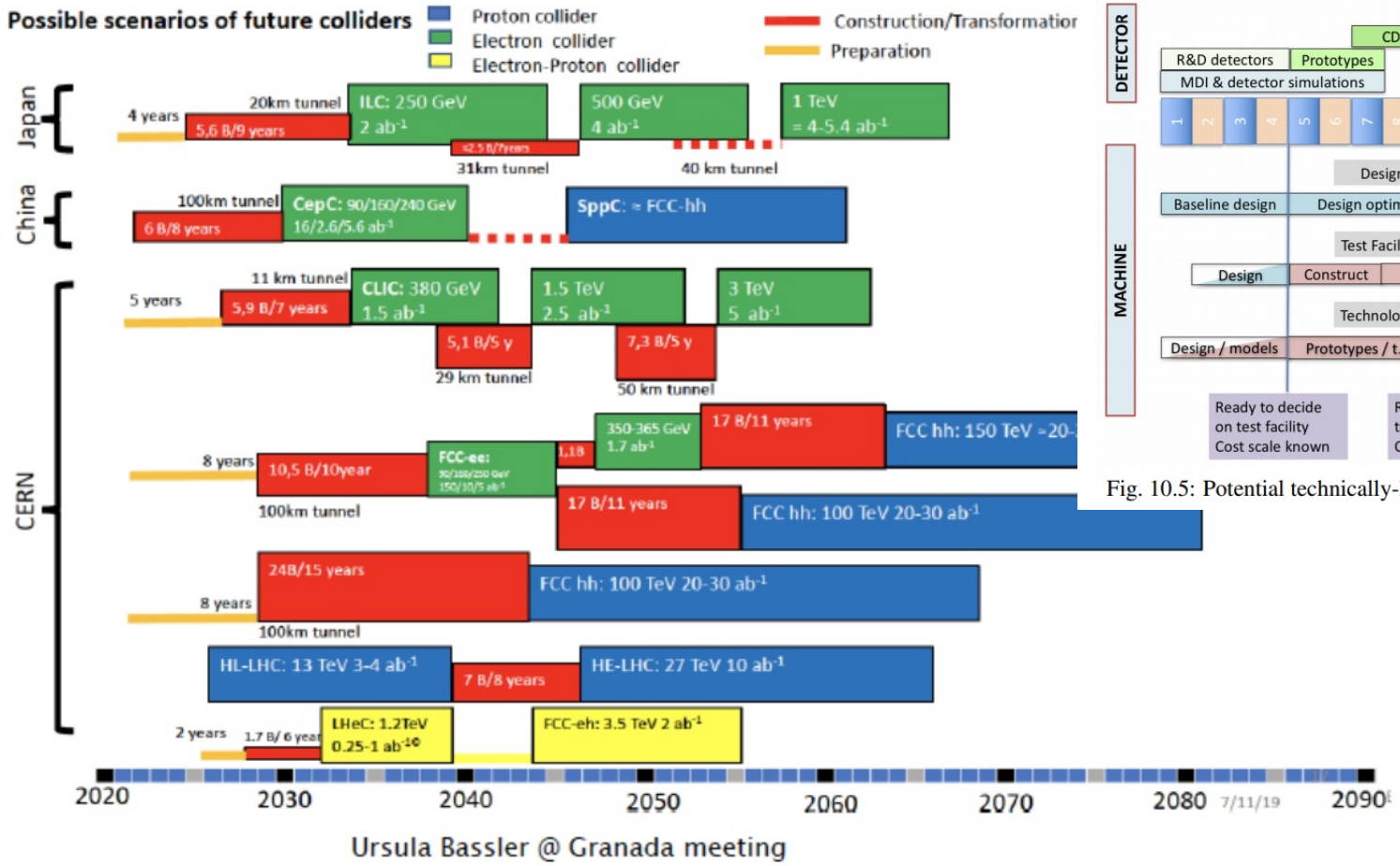
- European Strategy planning recently concluded
  - B. Heinemann RPM, June 25th

Particle Physics is global:

Snowmass process involves the international community and strategies/plans from other regions

- Strong support for an e^+e^- collider to study Higgs boson properties
- Encourages to develop a path towards a future energy-frontier machine
  - e.g. “investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV”, “an international design study for a muon collider”, etc..
  - Strong support for accelerator and instrumentation R&D
- Snowmass aims to build on top and expand such existing studies

Timescales



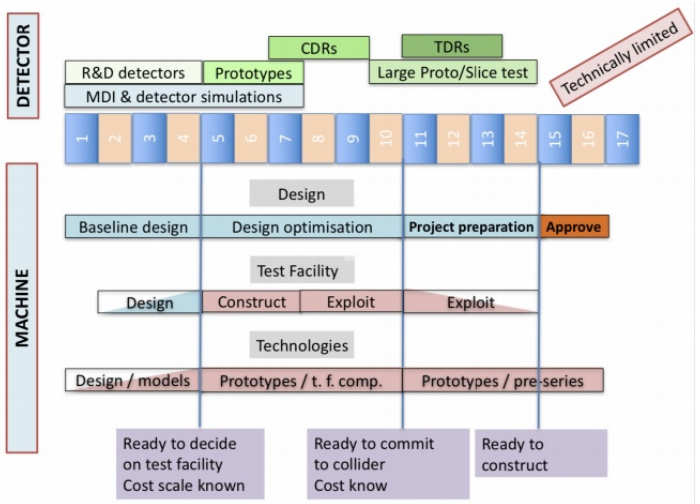
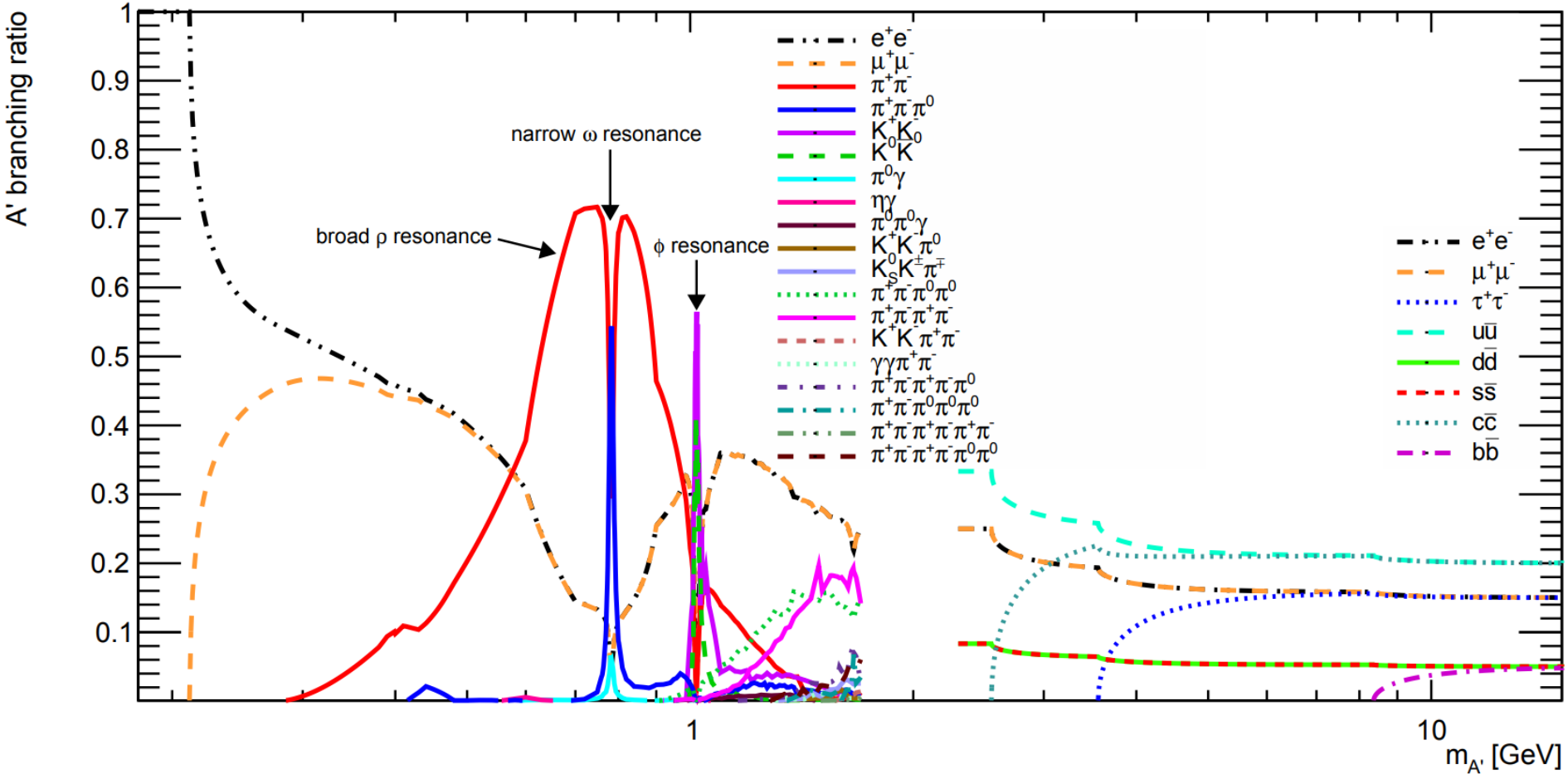


Fig. 10.5: Potential technically-limited time-line for a muon collider.

Including questions such as:
"what's the reach of an high-E machine after/if deviations are found in precision measurements either in lower energy colliders or other experiments?"

Dark photon branching ratios



arXiv:1505.07459