THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

Searches for the dark sector at accelerators

Christopher Hearty
U. British Columbia / IPP

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On behalf of the Belle II collaboration

DISCRETE 2024, LJUBLJANA, SLOVENIA

The most compelling question in particle physics

- Much of the universe is composed of matter that does not interact with photons, and is not consistent with the standard model.

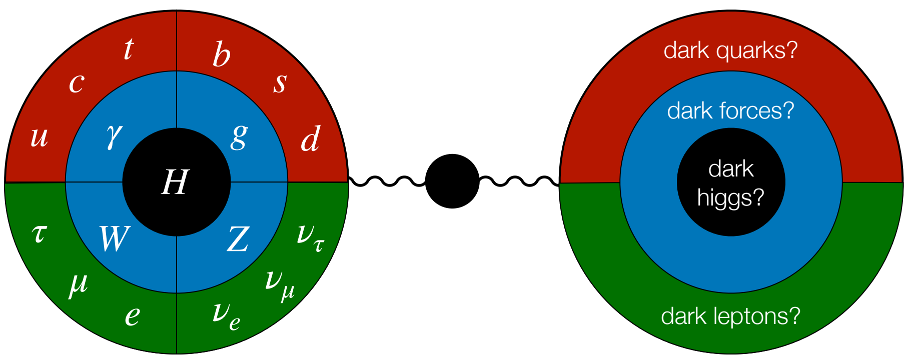
Cluster MACS J0025.4-1222. Blue shows mass distribution from gravitational lensing; red shows ordinary matter from x-ray imaging

NASA, ESA, CXC, M. Bradac, and S. Allen

- What is the particle nature of dark matter?

The dark sector

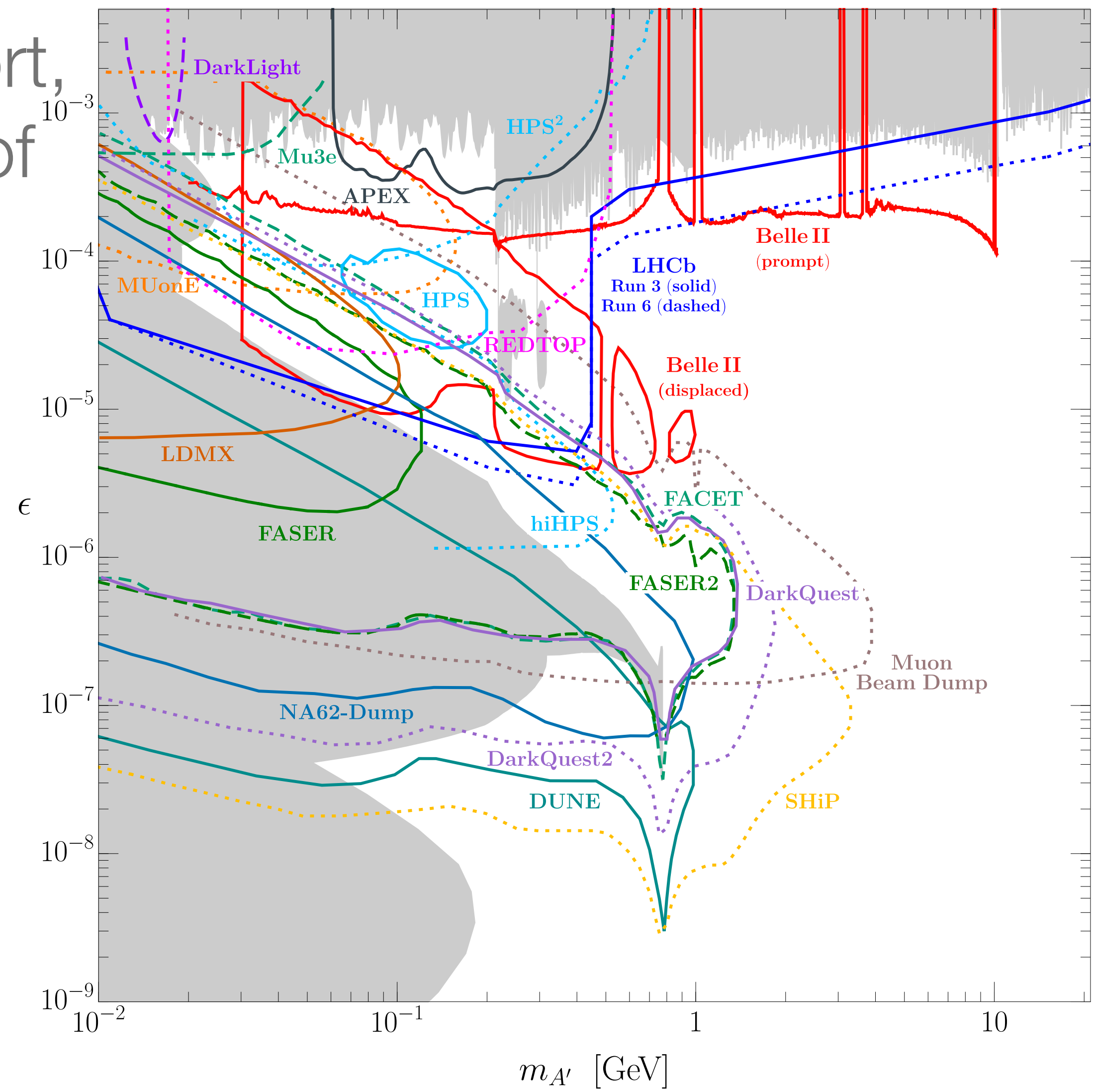
- Currently, there is considerable focus on “dark sector” models of dark matter.
  - Dark matter particles are light, typically < few GeV/c^2
  - Requires new dark force carriers, which have feeble interactions with the standard model.



Gori, Williams et al,
arXiv 2209.04671 (2022)

Searching for the dark sector in the laboratory

- Extensive, world-wide effort, including a large number of dedicated projects.



Batell, Blinov, Hearty, McGehee,
arXiv 2207.06905 (2022)

Outline

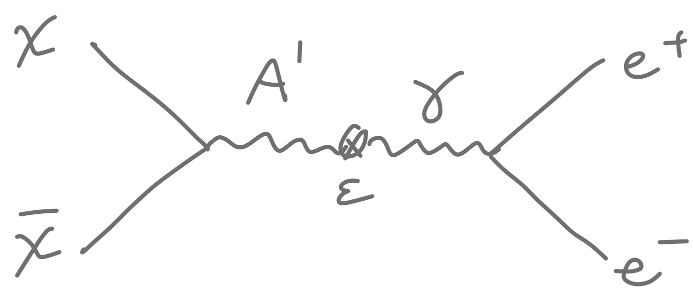
- Dark photon
- Axion-like particles
- L_μ - L_τ Z'
- B-mesogenesis

Dark photon

Dark matter / dark sector / dark photons

- Particularly straightforward model: dark matter χ plus dark photon A′, which mixes with strength ε with the γ.

- Dark matter is in thermal equilibrium in the early universe



and vice-versa

Different process if $m_\chi > m_{A'}$; less predictive

- The resulting dark matter relic density depends on the parameter $y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$; there are specific combinations of parameters that give the observed value.

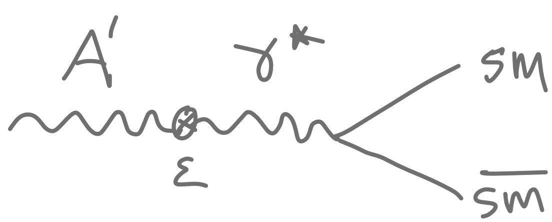
coupling of dark photon to dark matter, $\mathcal{O}(1)$

Dark photon production and decay

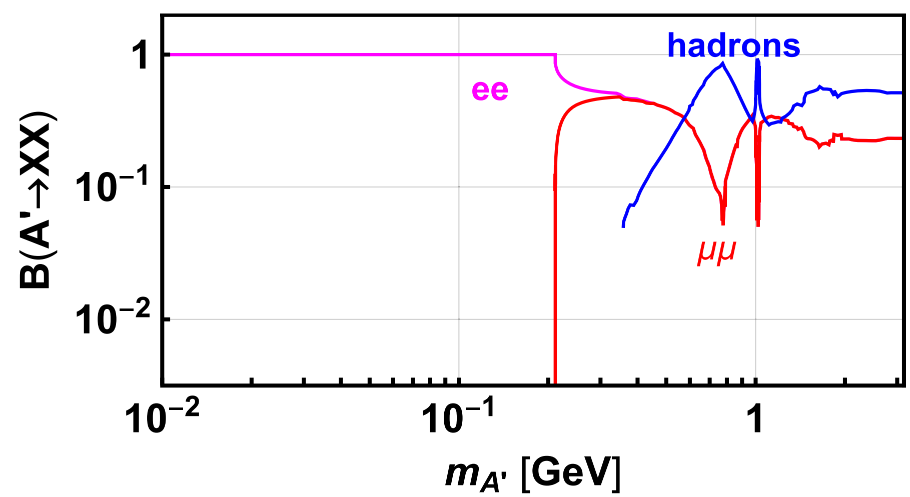
- Wide range of production mechanisms for dark photons at accelerators (≈ energetic photon).
- If kinematically allowed $m_{A'} > 2m_{\chi}$, dark photon decays to dark matter (~100%).

"invisible"

- Otherwise, dark photon decays like a virtual photon of mass $m_{A'}$.

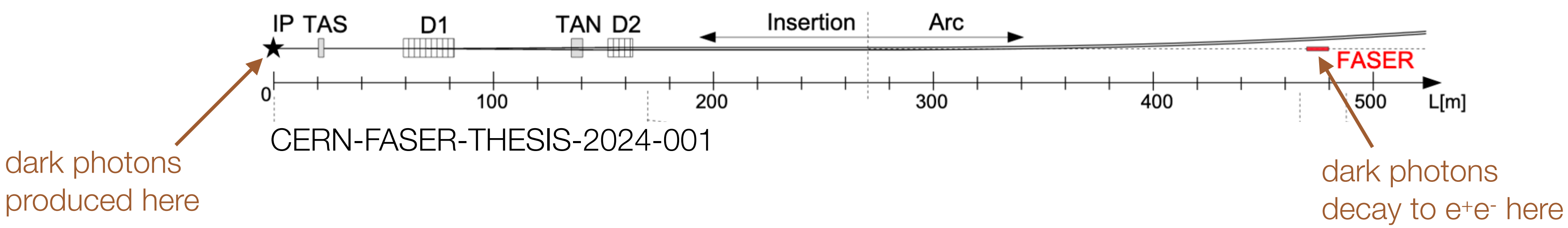


"visible"



Search for dark photons decaying to e+e- at FASER

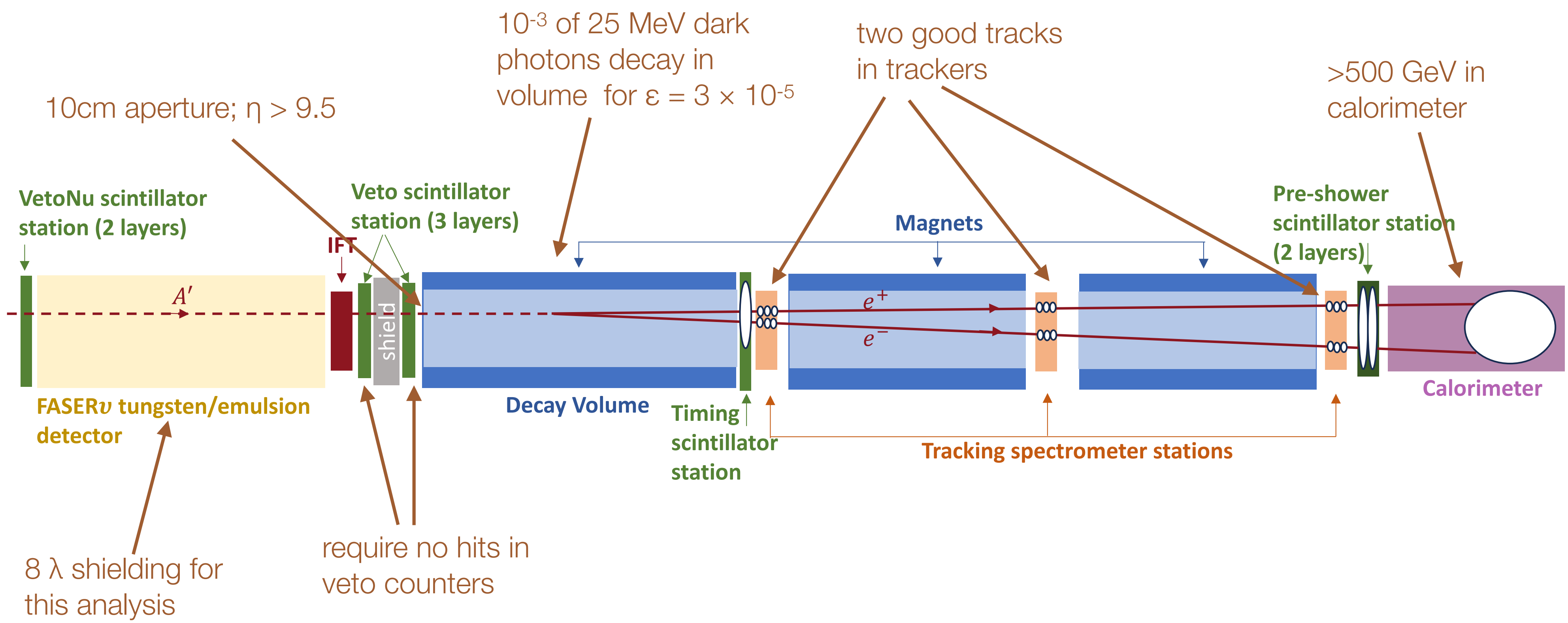
- FASER is located 480m downstream of ATLAS, at the Large Hadron Collider at CERN. On the beam axis, shielded by 100m of rock & concrete.



CERN-FASER-THESIS-2024-001

- Dominant A′ production mechanism is via meson decay, $\pi^0/\eta \rightarrow \gamma A'$ (low p_t). Decays 100% to e+e-.

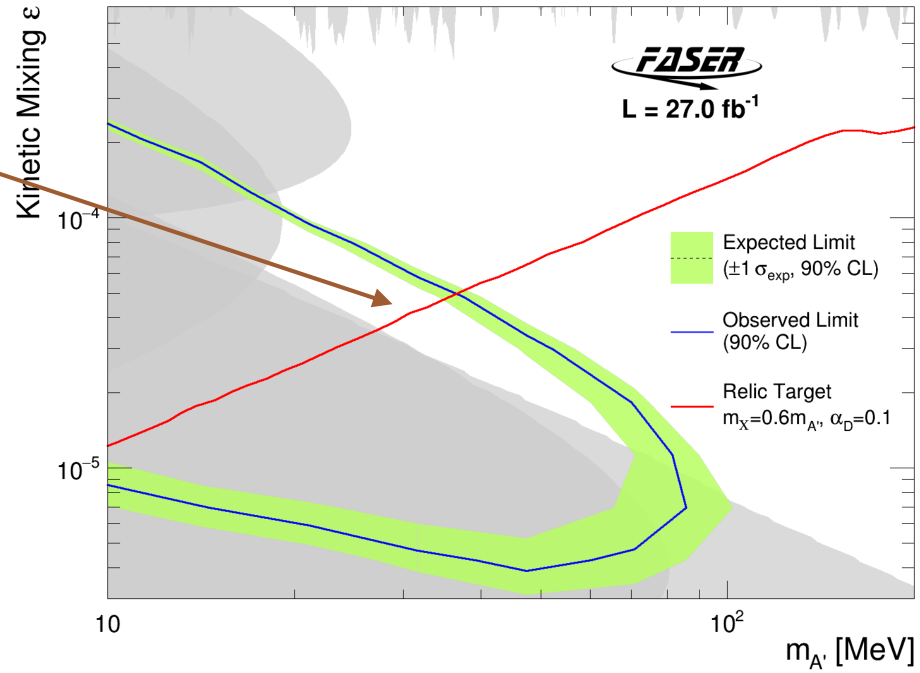
Overview of detector and analysis



- Expected background $(2.3 \pm 2.3) \times 10^{-3}$ events.
  - K_L^0 produced by muons in rock; ν interactions.
  - well designed special-purpose detector.

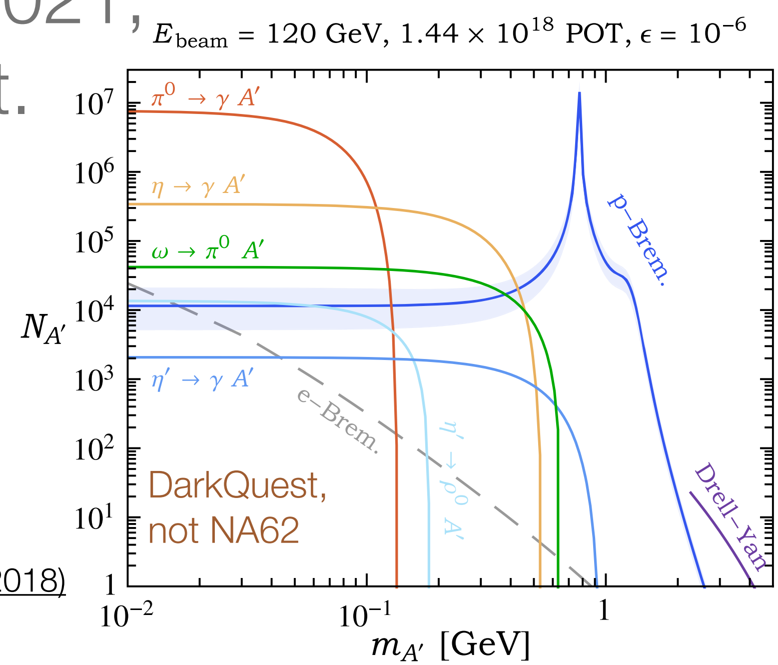
- No events observed in 27.6 fb^{-1} at 13.6 TeV. Expect ~8× more data by end of Run 3 (2025).

Analysis is sensitive to parameter space that would explain astronomical dark matter



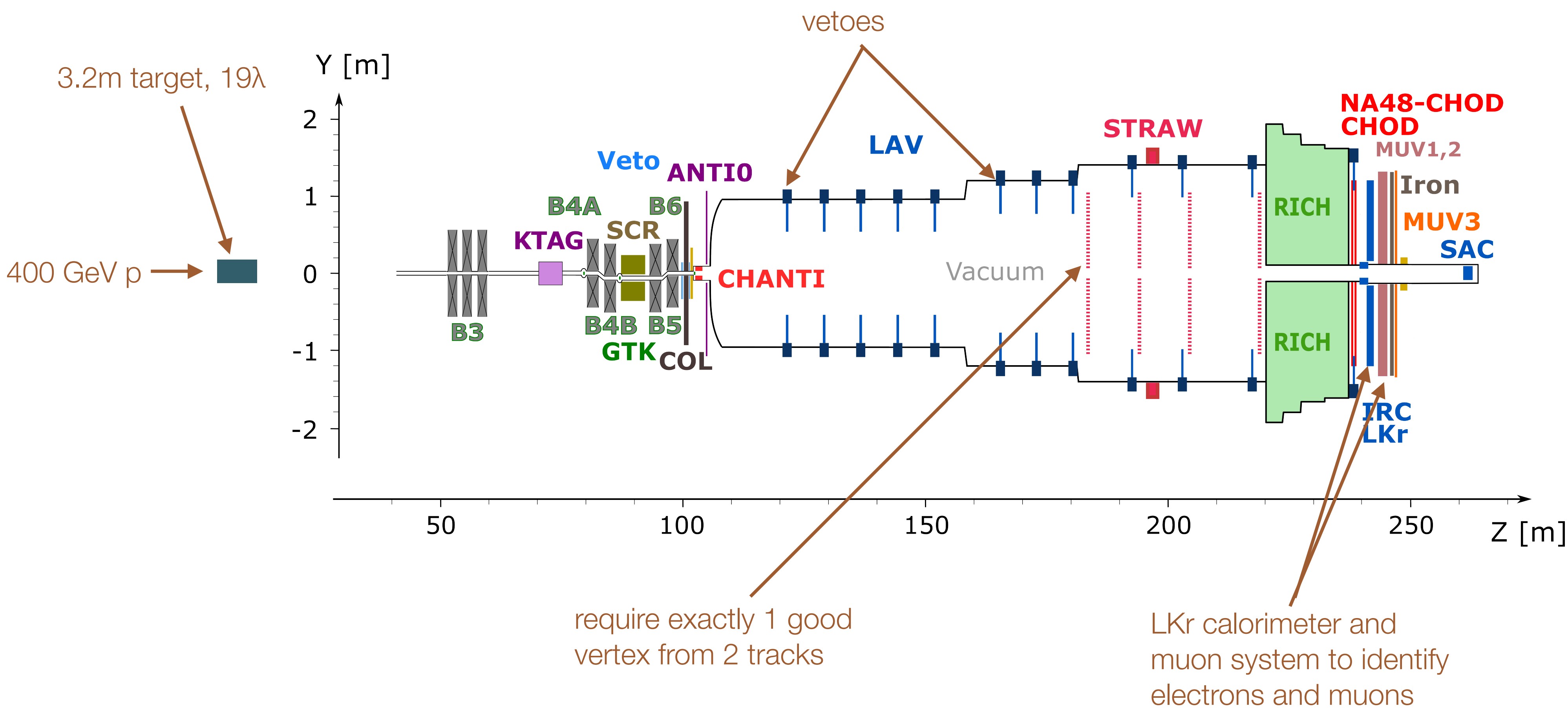
NA62 — search for dark photons decaying to e^+e^- (or $\mu^+\mu^-$)

- Primary goal of NA62 is the study of the ultra-rare decay $K^+ \to \pi^+ \nu \bar{\nu}$. CERN north area, SPS beam.
- Data also collected in special configuration "dump mode" for dark photon search. 10 days in 2021, 1.4×10^{17} 400-GeV protons on target.
- Meson decay and bremsstrahlung



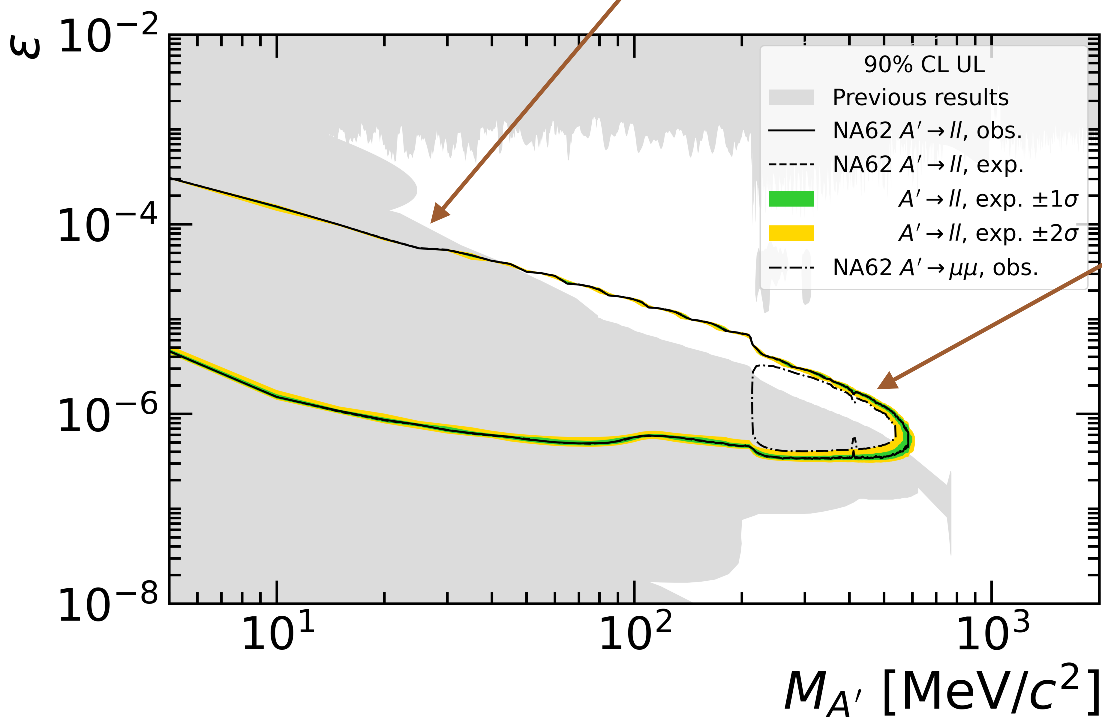
Berlin, Gori, Schuster, Toro, PRD 98, 035011 (2018)

Detector and analysis overview



- Very clean: predict ~0.01 background
  - muons striking (e.g.) vetoes and producing secondary vertices. No events found.

FASER



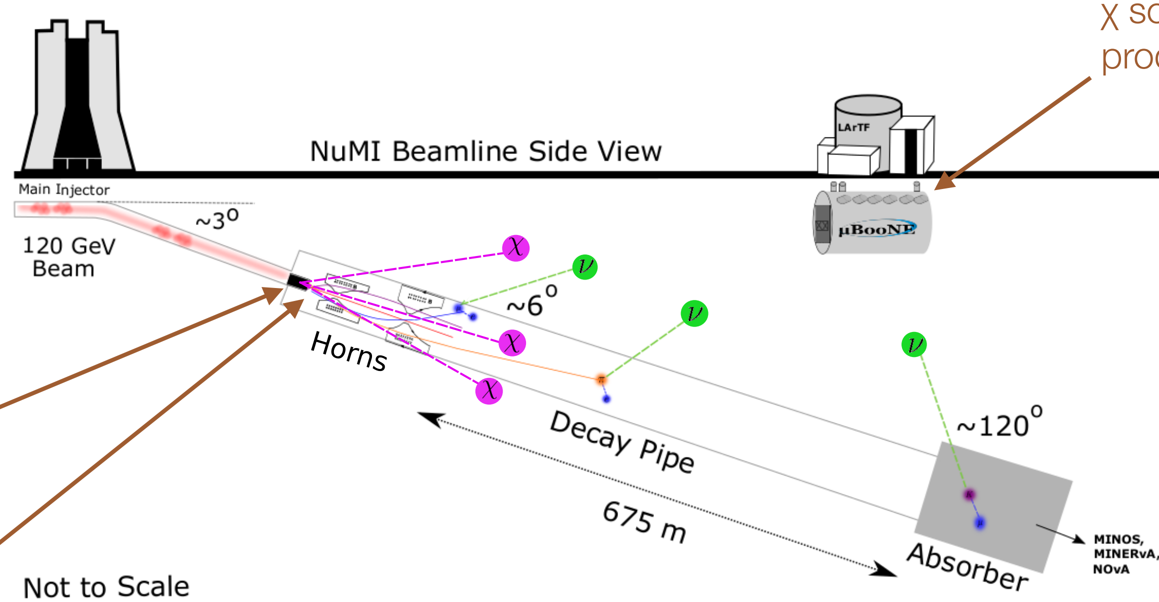
Bremsstrahlung production gives higher mass reach than FASER despite much lower center of mass energy

see also NA62 JHEP 2023, 35 (2023) for previous $\mu^+\mu^-$ results

Dark Tridents at MicroBooNE

- Liquid argon TPC (85 t), part of the Fermilab short baseline neutrino program.

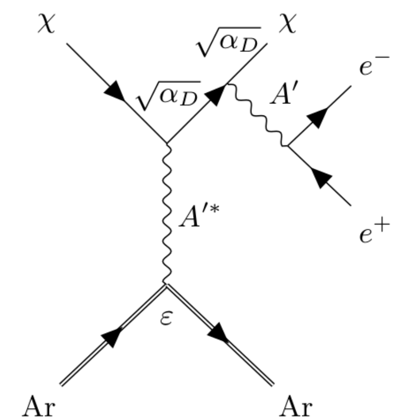
fermilab-thesis-2024-02



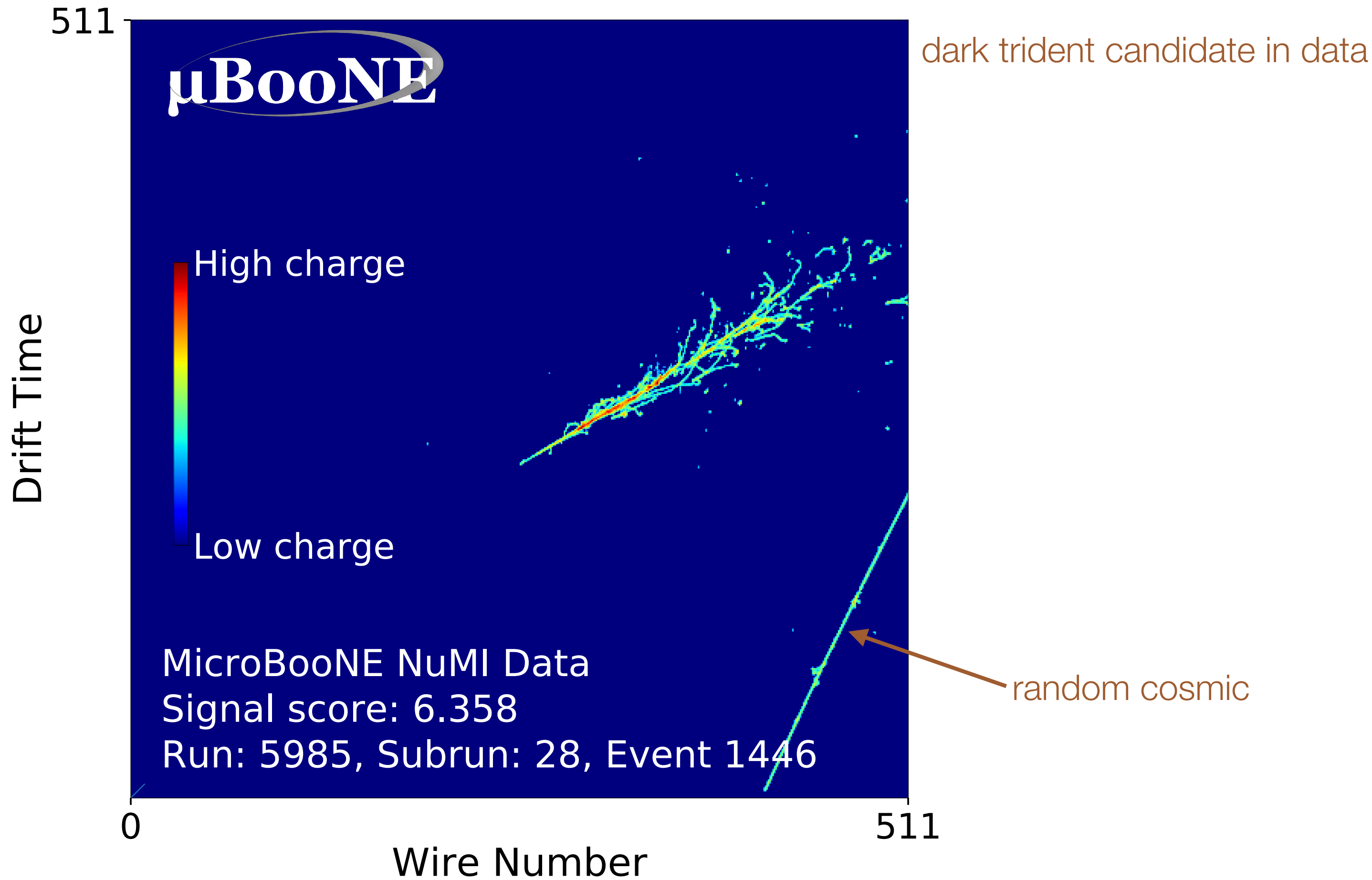
χ scattering in LAr produces $A' \to e^+e^-$

120 GeV protons on 1m graphite target

dark matter production via $\pi^0 \to \gamma\chi\bar{\chi}$ (off-shell dark photon)

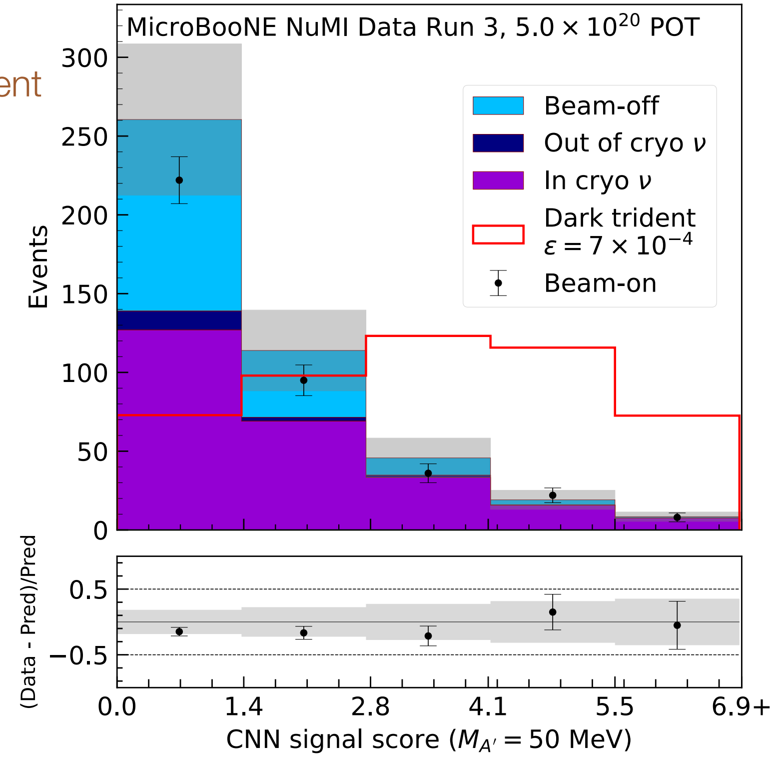


- Signal $\propto \varepsilon^4 \alpha_D^3$. But 7.2×10^{20} protons on target.

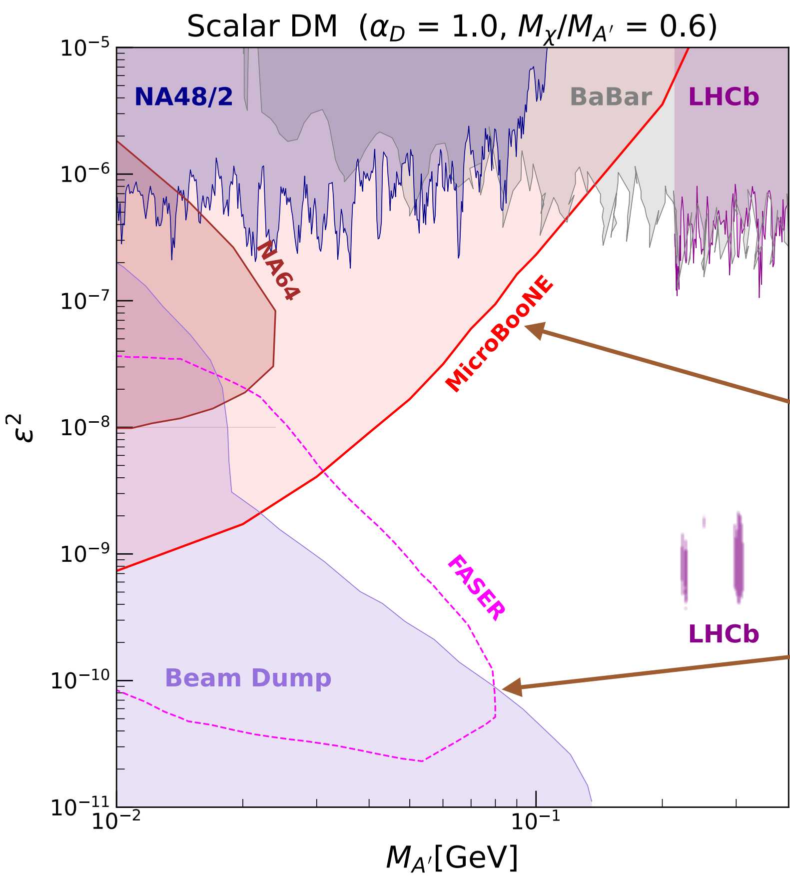


- Convolutional neural net trained on simulated signal and background (mostly π^0 from ν).

CNN score in data is consistent with background expectation



Limits depend on nature of DM, α_D, and mass ratio



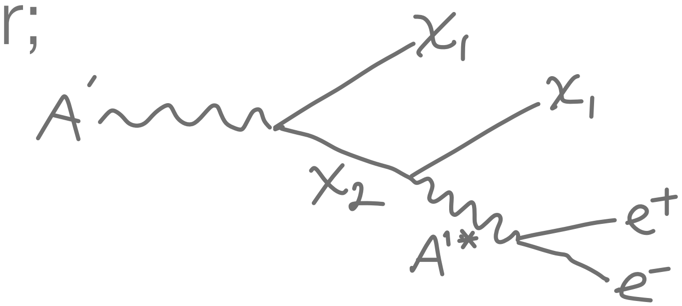
MicroBooNE is sensitive to short A′ lifetimes

FASER to long lifetimes

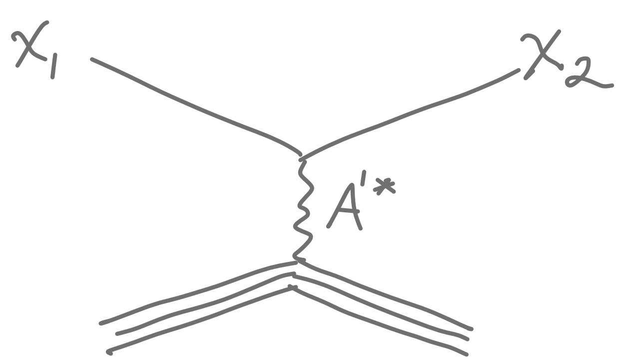
Inelastic dark matter — semi-visible

- Dark photon could couple to a pair of particles $\chi_1\chi_2$.
  - χ_1 is the astronomical dark matter;
  - χ_2 is slightly heavier, and decays

  to χ_1 plus standard model particles.



- Can explain the observed dark matter relic density, and also the lack of a signal in direct detection.



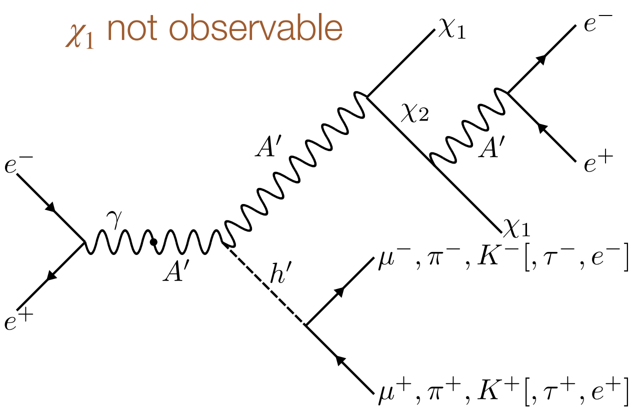
production of heavier χ_2 is kinematically forbidden for low-momentum χ_1.

Inelastic dark matter plus dark Higgs at Belle II

- Belle II physics includes direct searches for feebly interacting low-mass particles. Dedicated low-multiplicity triggers: single photon, single track, single muon.

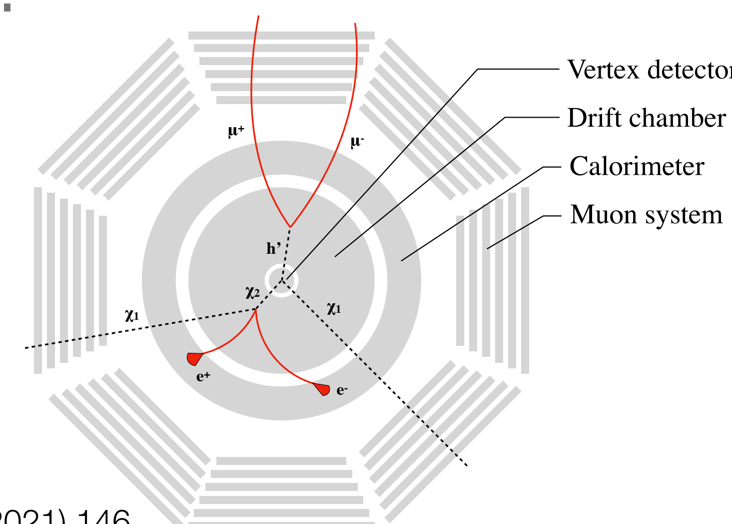
- Assume that the dark sector includes a dark Higgs h′. Mixes with strength θ with the Higgs.

χ_1 not observable



trigger on calorimeter energy from e^+e^-; displaced vertex trigger under development

reconstructs to h′ mass

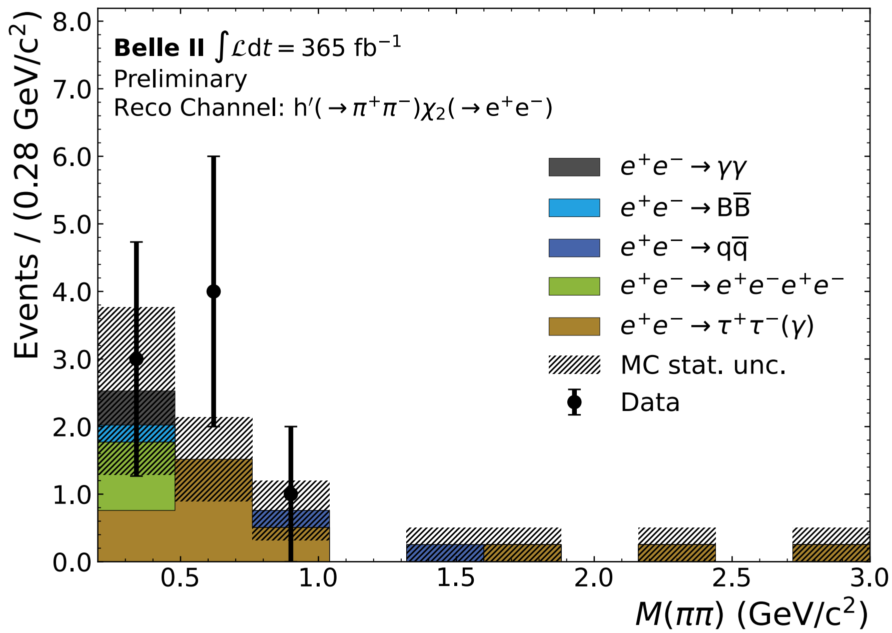


Duerr, Ferber et al, JHEP04 (2021) 146

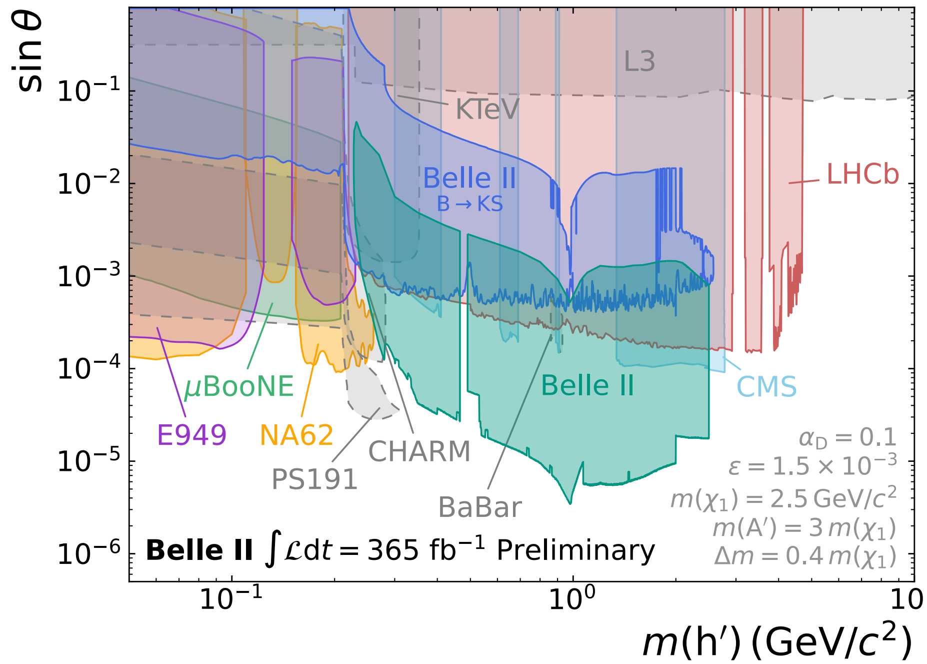
- Very low backgrounds; displaced vertex plus energetic e^+e^- pair with opening angle not consistent with a $\gamma \to e^+e^-$ conversion.

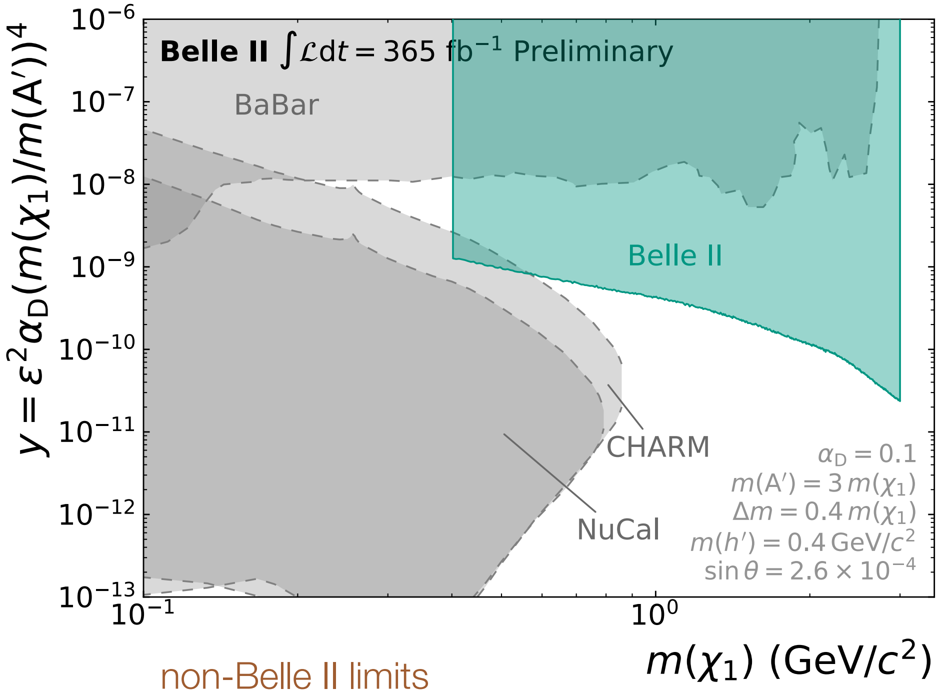
9 events observed, consistent with expected background.

8 of 9 are $\pi^+\pi^-$



- Strong limits, but dependence on 5 other parameters.





non-Belle II limits
do not require h′

Axion-like particles

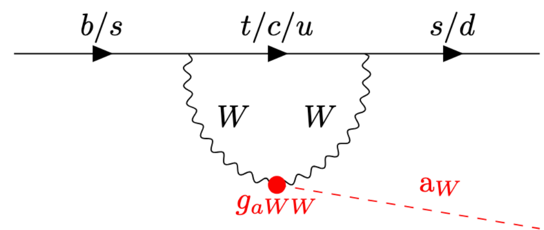
Axion-like particles

- Axions were proposed to explain why QCD does not violate CP. Axion-like particles have the same quantum numbers, but wider range of masses and couplings, typically to standard model gauge bosons.

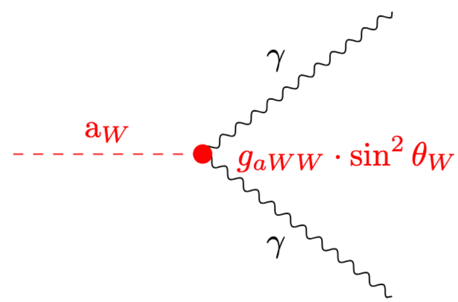
- Could be the mediator to dark matter.

Search for axion-like particles decaying to γγ in FASER

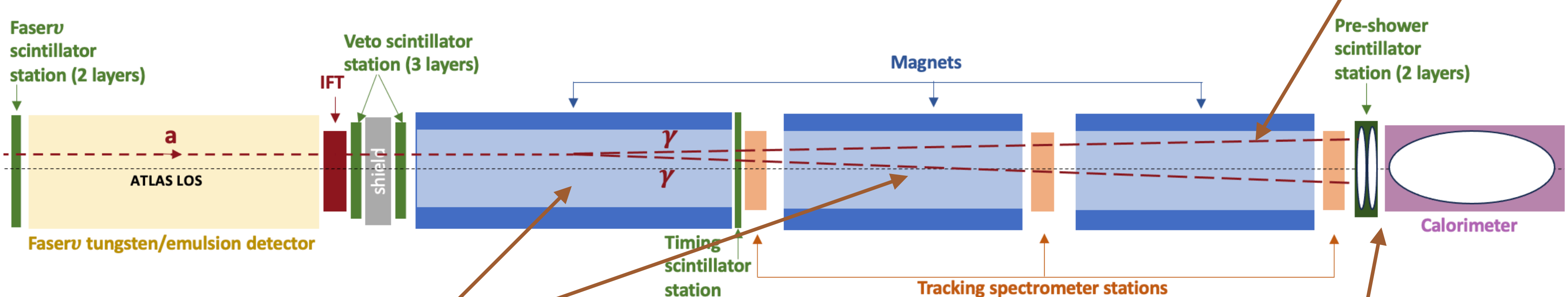
- Focus on ALP that couples to W. Dominant source is $B \to K a_W$.



- Decay is 100% to $\gamma\gamma$.



can't actually distinguish the two photons



acceptance 10^{-7} — 10^{-6}

require >1.5 TeV in calorimeter, consistent energy distribution in two preshower layers

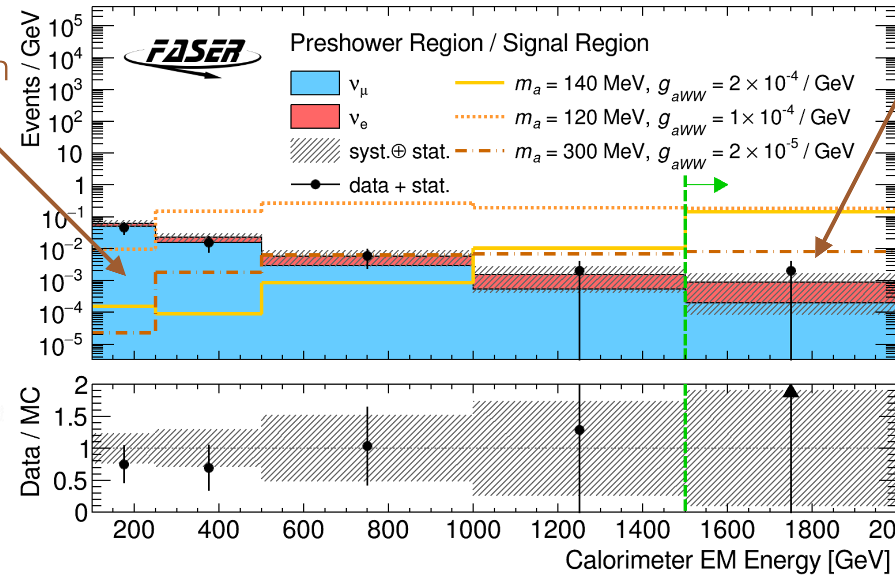
FASER arXiv 2410.10363 (2024)

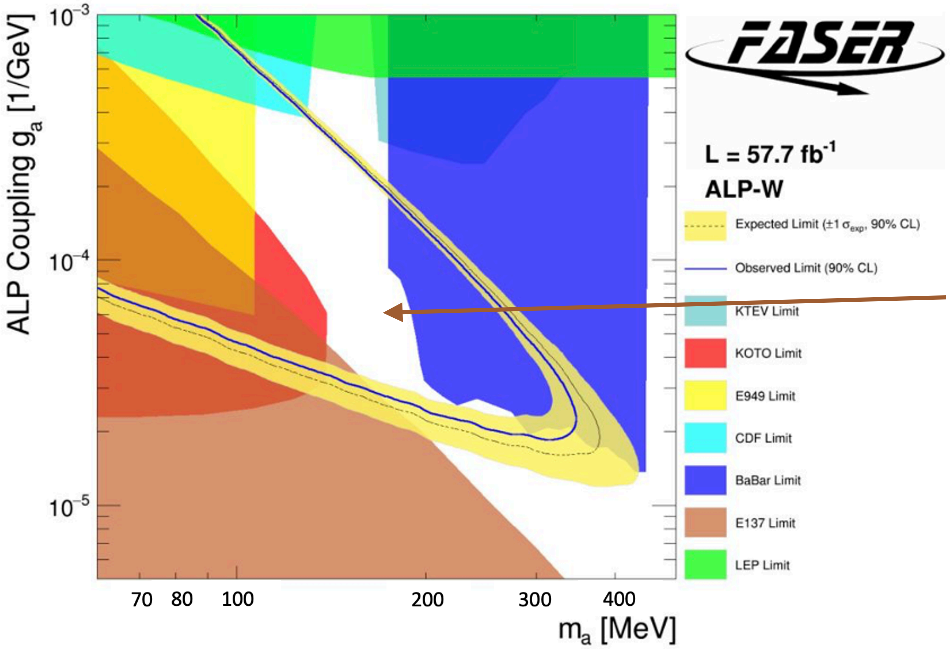
forward production of B mesons

- Expect 0.44 ± 0.39 background from ν interactions. One observed.
  - study using preshower & calorimeter sidebands.

signal region

mc prediction



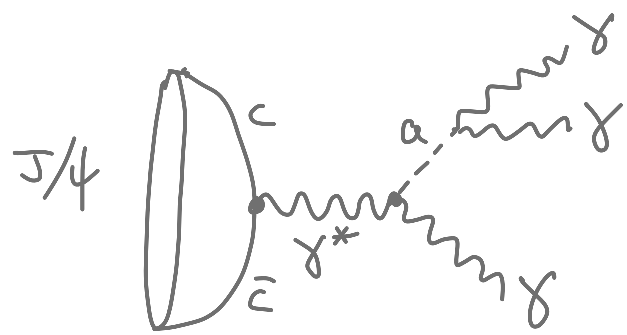


unexplored parameter space excluded

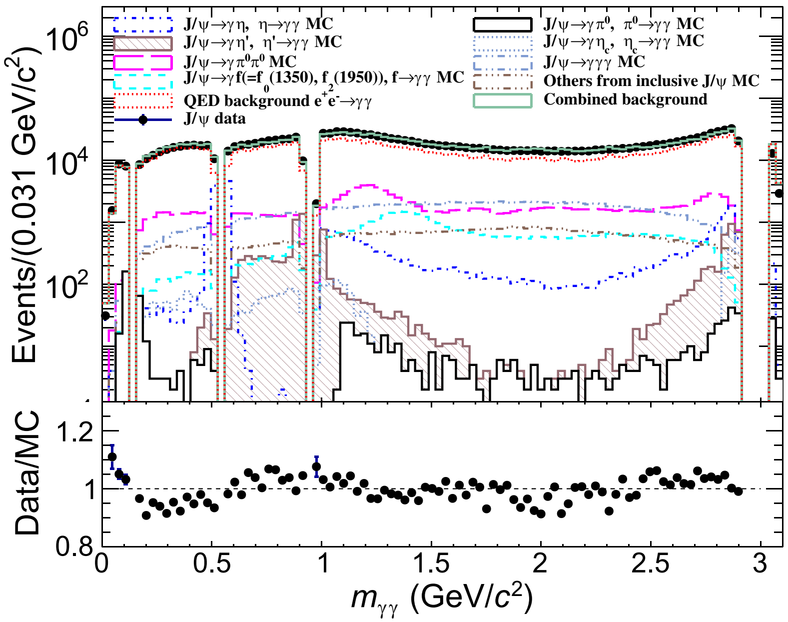
- Upgraded preshower with two photon resolution should be ready in 2025.

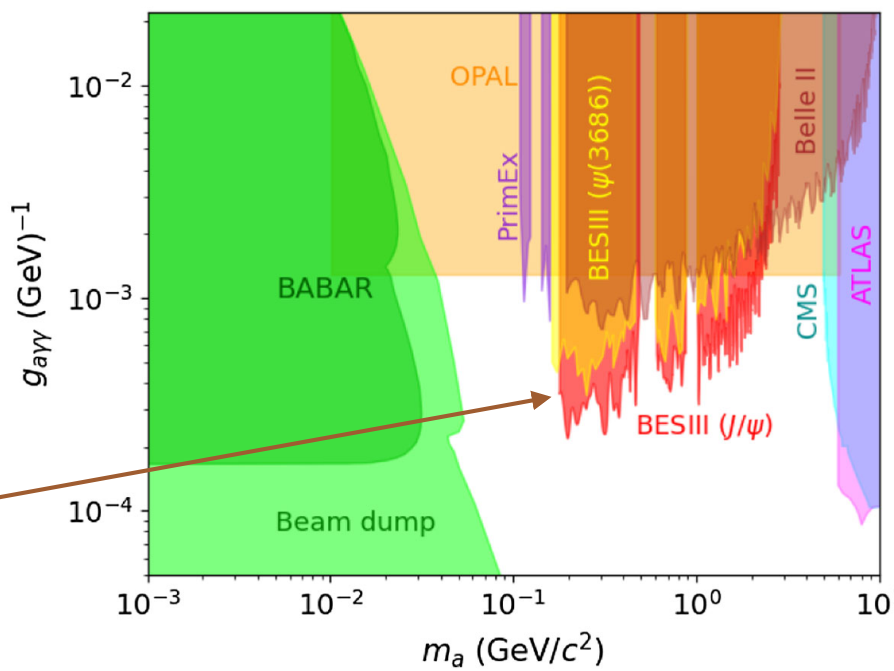
BESIII: Search for axion-like particle production in J/ψ decay

- BESIII collected 10^{10} J/ψ in 2009 and 2012.
- Focus on ALP with dominant coupling to photons. Final state is 3 photons with no missing energy.



- Large background $e^+e^- \to \gamma\gamma\gamma$, plus (e.g) 10^7 $J/\psi \to \gamma\eta$ (control sample).





World leading results for $0.18 < m_a < 2.85$ GeV/c^2

L_μ - L_τ Z′

The L_μ - L_τ model

- I motivated this talk with dark matter. But perhaps there are other hints of new physics.
  - Muon anomalous magnetic moment $(g-2)_\mu$;
  - Observables in the B system, e.g. angular distributions in $B \to K^{(*)}\mu^+\mu^-$.
- The L_μ - L_τ model includes a gauge boson Z′ that couples only to mu or tau leptons or neutrinos.
  - could also couple to dark matter.

NA64μ

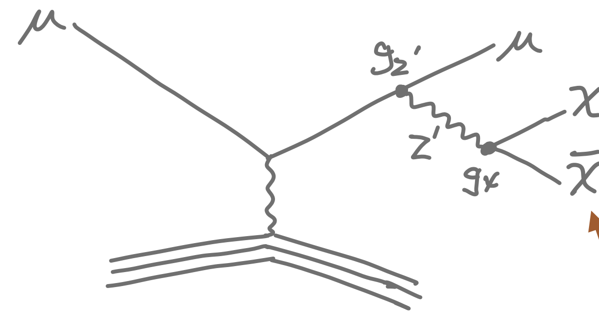
- NA64 is a fixed target experiment in the CERN SPS beam line dedicated to dark sector searches.

- Extensive, world-leading results with 100 GeV electrons; demonstration results with positrons.

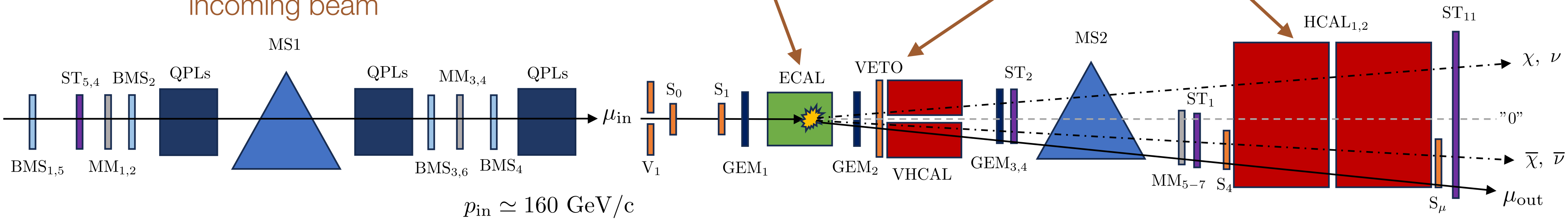
- Most recently, data collected with 160 GeV/c muons to focus on new physics related to the muon sector.
  - 2×10^{10} muons on target, average of 2.5μs between particles.

NA64 search for invisible decays of the Z′ using a muon beam

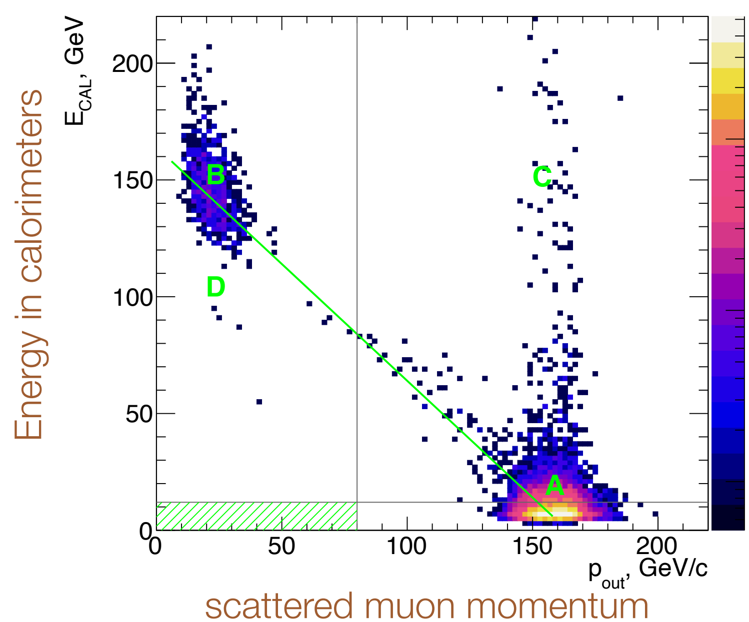
- Signature: 160 GeV/c μ into target; μ with <80 GeV/c out with large missing energy.

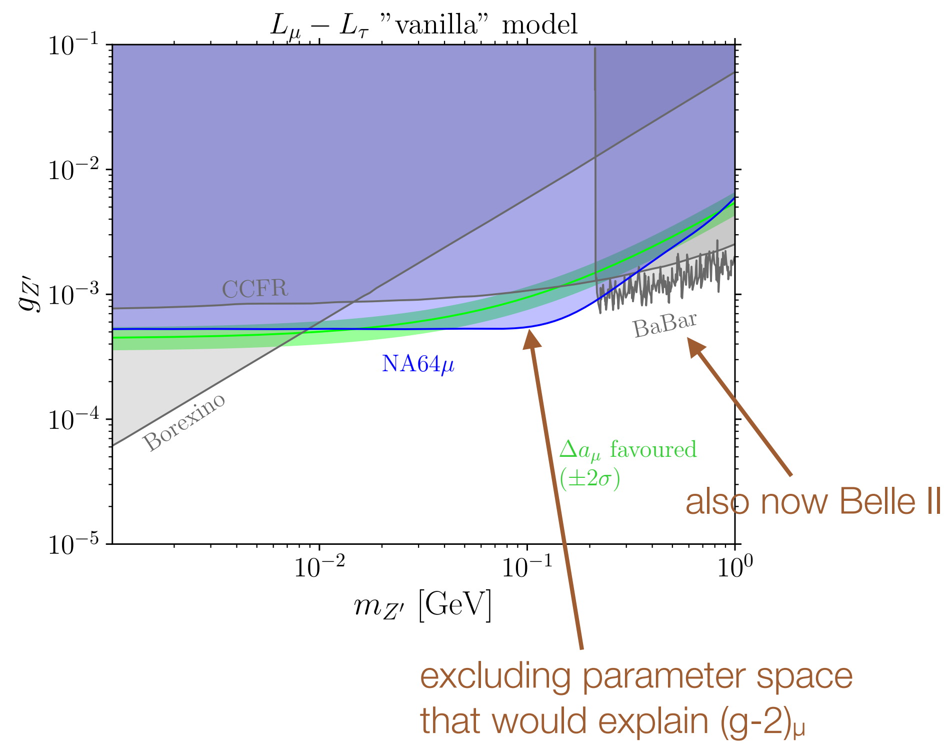


or neutrinos



- Expect background of 0.07 ± 0.03 events
  - low-side tail on momentum measurement
  - $K^+ \rightarrow \mu^+\nu_\mu$ from 10^{-5} contamination in muon beam

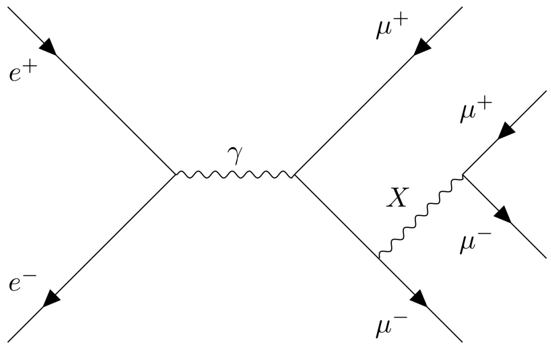




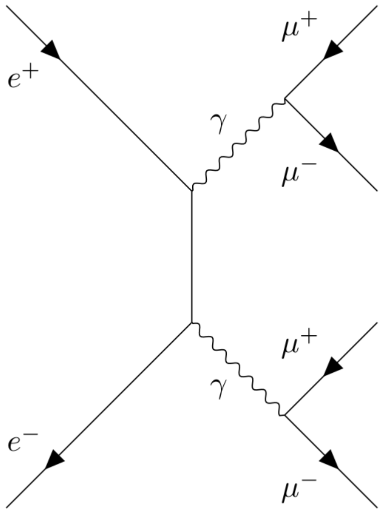
- Future: 2nd spectrometer and faster detectors would enable 40× higher event rate.

Belle II: search for an L_μ - L_τ Z' decaying to $\mu^+\mu^-$

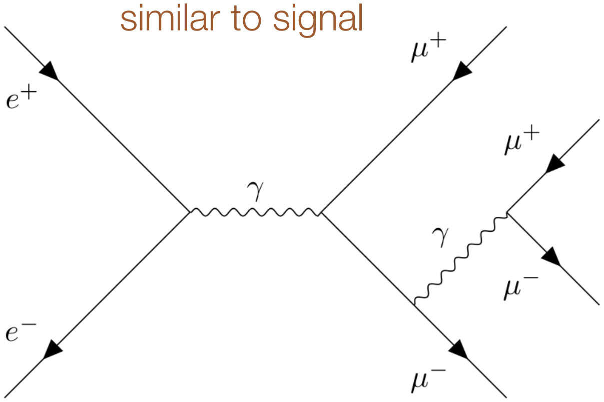
- Resonance in 4μ final state.
- Same signature for a muonphilic scalar. Created to explain $(g-2)_\mu$.



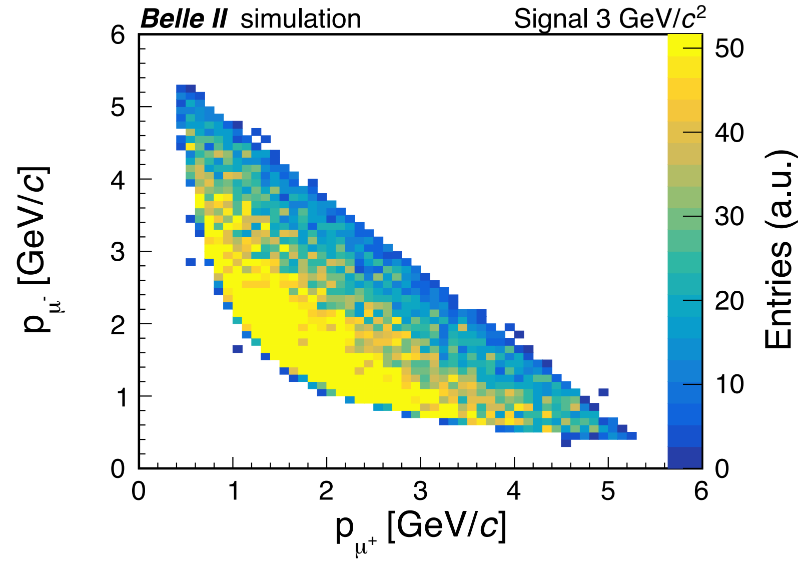
- Large standard model production of $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$:

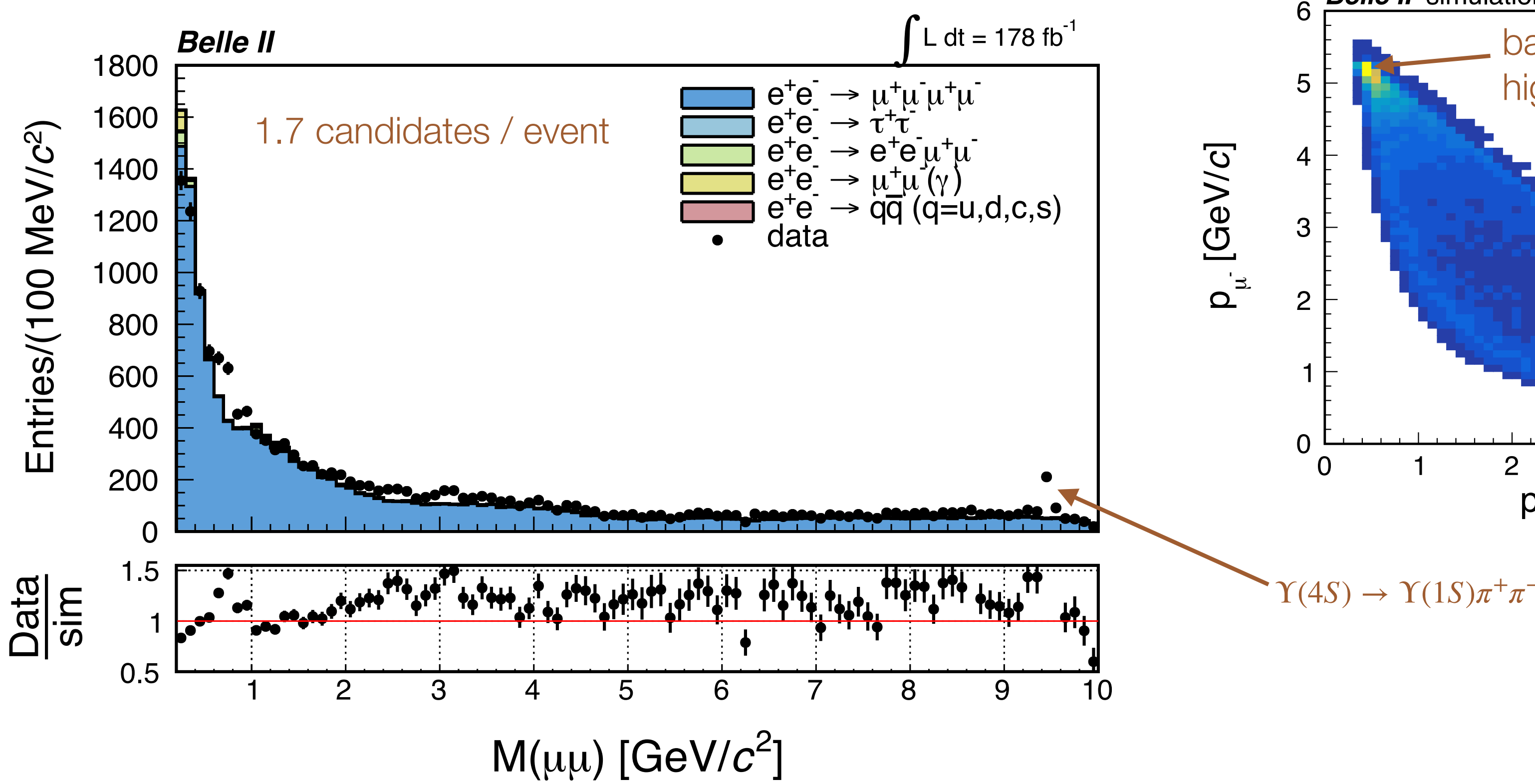


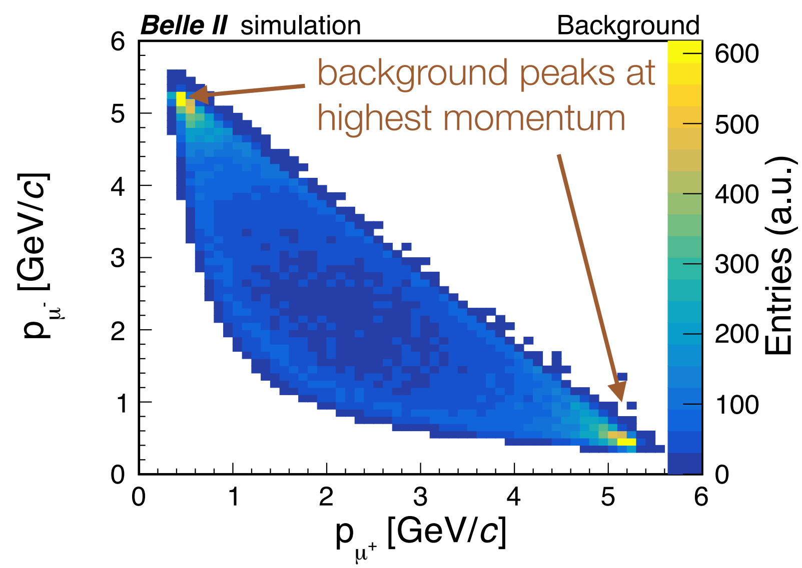
subdominant, but kinematically similar to signal



- Key: exploit kinematic differences between the signal (i.e. final state radiation) and most of the background in a neural net.
  - trained on Z′, applied to scalar.

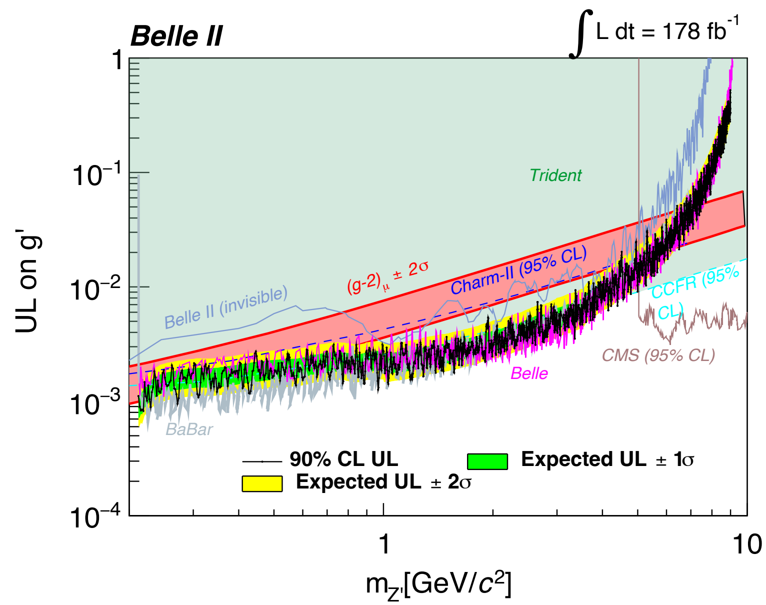


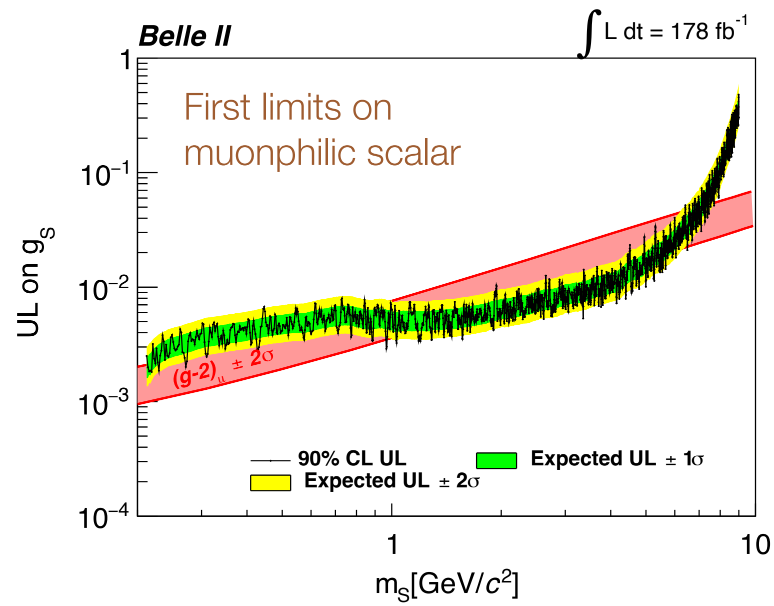




- Z′ limits are comparable to BaBar with 1/3rd of the luminosity due to machine learning discriminator.

- First limits on muonphilic scalar; exclude part of $(g\text{-}2)_\mu$ parameter space.





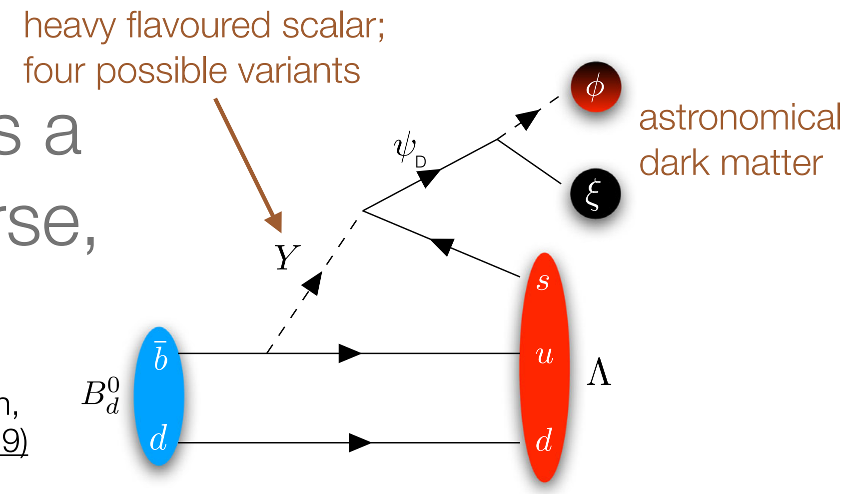
B-mesogenesis

BaBar PRL 131, 201801 (2023)
BaBar PRD 107, 092001 (2023)

BaBar: searches for baryogenesis and dark matter (parallel session on Tuesday)

- B mesons can decay to a dark baryon ψ_D and a baryon.
- CP violation in B^0 mixing produces a baryon excess in the visible universe, and an anti-baryon excess in the dark sector.

Elor, Escudero, Nelson, PRD 99, 035031 (2019)



- Limits in 3 of 4 modes; first limits for p and Λ_c^+.
  - $\mathscr{B}(B^+ \to p\psi_D) < 10^{-6} - 10^{-5}$
  - $\mathscr{B}(B^0 \to \Lambda\psi_D) < (0.13 - 5.2) \times 10^{-5}$
  - $\mathscr{B}(B^+ \to \Lambda_c^+\psi_D) < 1.6 \times 10^{-4}$ (preliminary)

Strongly constrains "basic" model for these 3 modes.

Summary

- Wide range of experiments at accelerators searching for dark sector particles, including dark photons, axion-like particles, dark scalars, and Z'.
  - dedicated detectors, general purpose experiments at colliders, neutrino experiments.

- These experiments are exploring models and parameter space that would explain astronomical dark matter and produce observable signatures in the laboratory.

- More on the way… FASER, Belle II, LHCb phase 2.