TEXAS A&M UNIVERSITY
Mitchell Institute

LIGHT DARK WORLD 2026
July 28th - July 31st
Carleton University
Ottawa, Canada

# Can the LHC be sensitive to the Light Dark World?

July 29, 2026

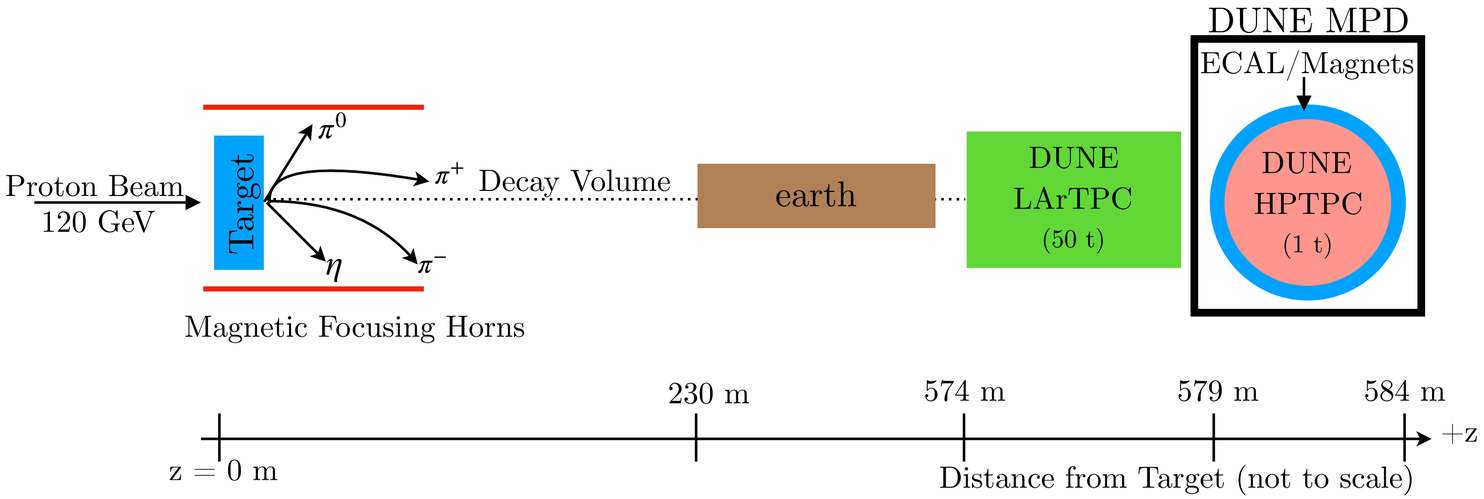
Deepak Sathyan

Ongoing work with Bhaskar Dutta, Aparajitha Karthikeyan, Doojin Kim, Hyunyong Kim, Taehee Kim

# Probing light mediators

- Light mediators produced in abundance at fixed target experiments

# Probing light mediators




[1912.07622] Berryman, de Gouvêa, Fox, Kaysey, Kelly, Raaf

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- DUNE Near Detector: 120 GeV proton beam hits fixed target

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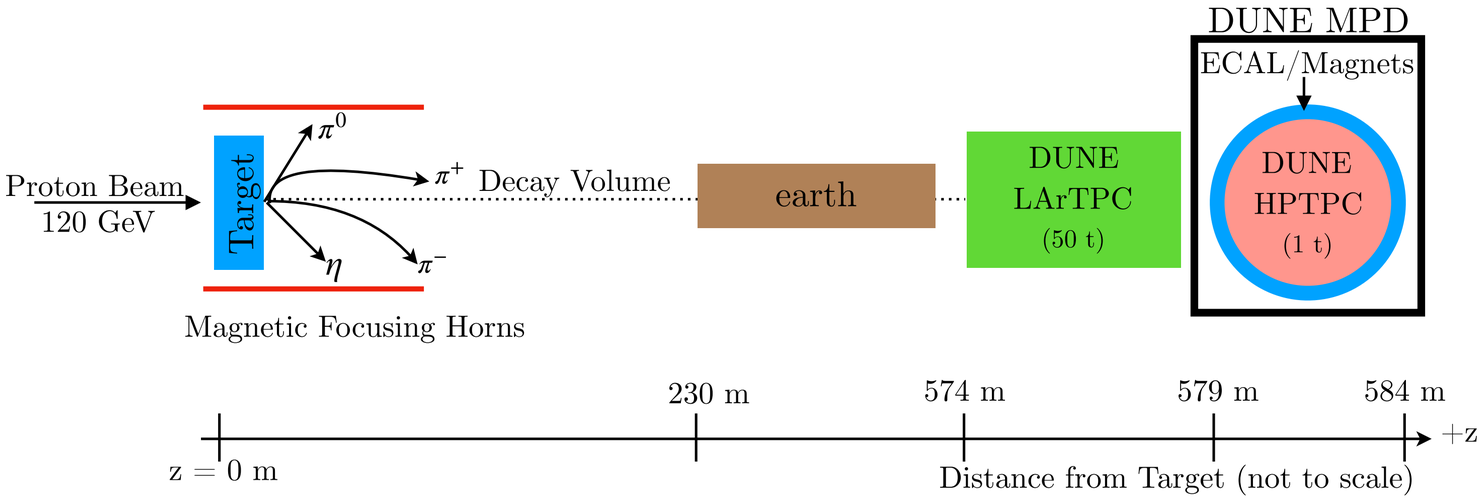


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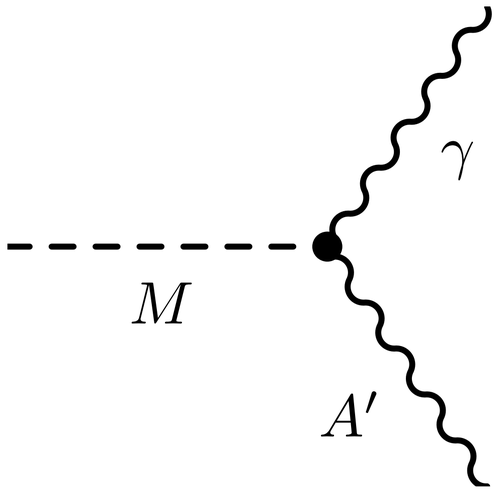


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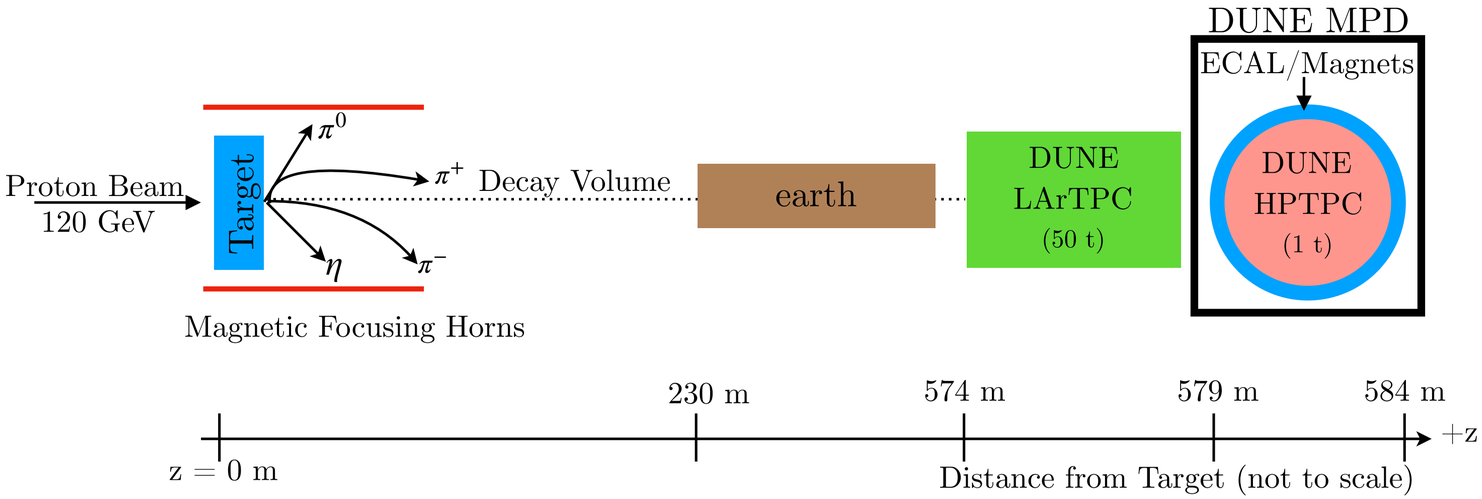


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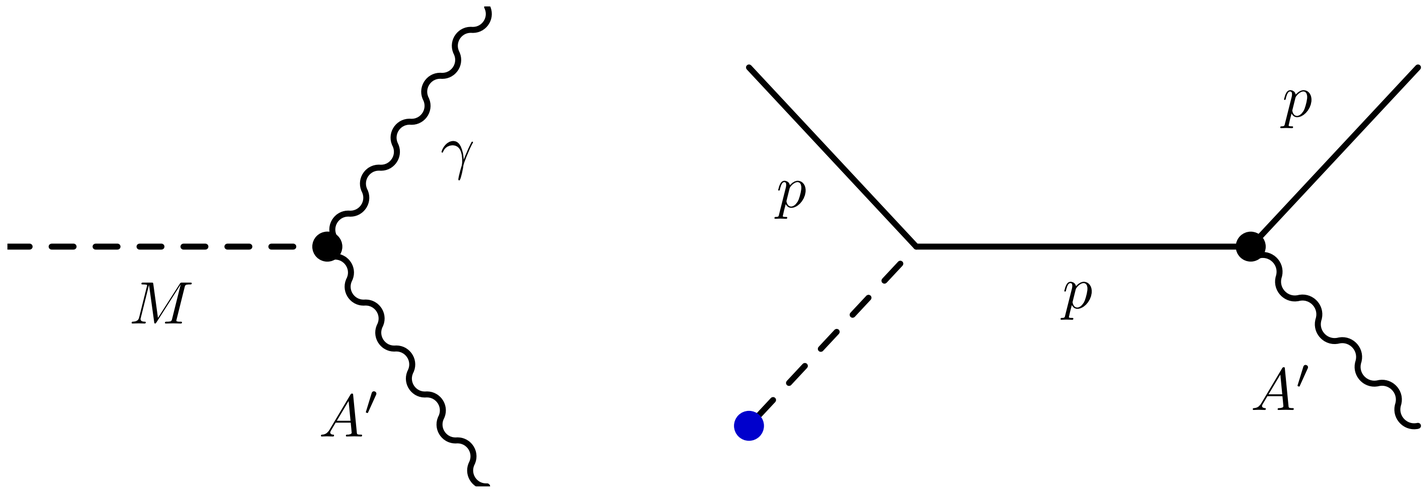


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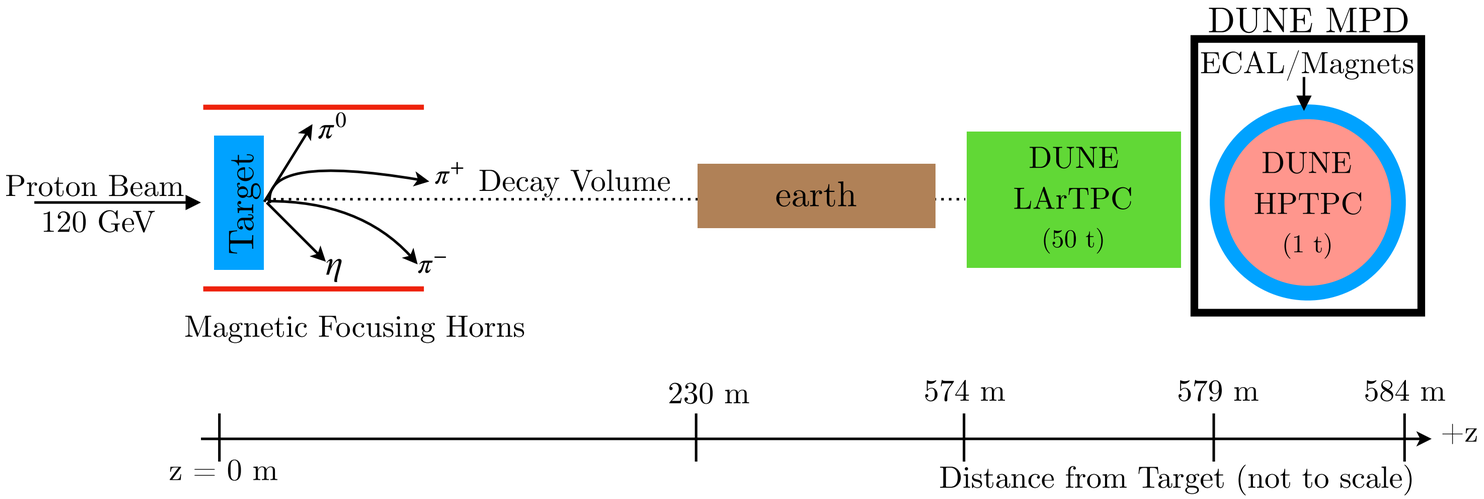


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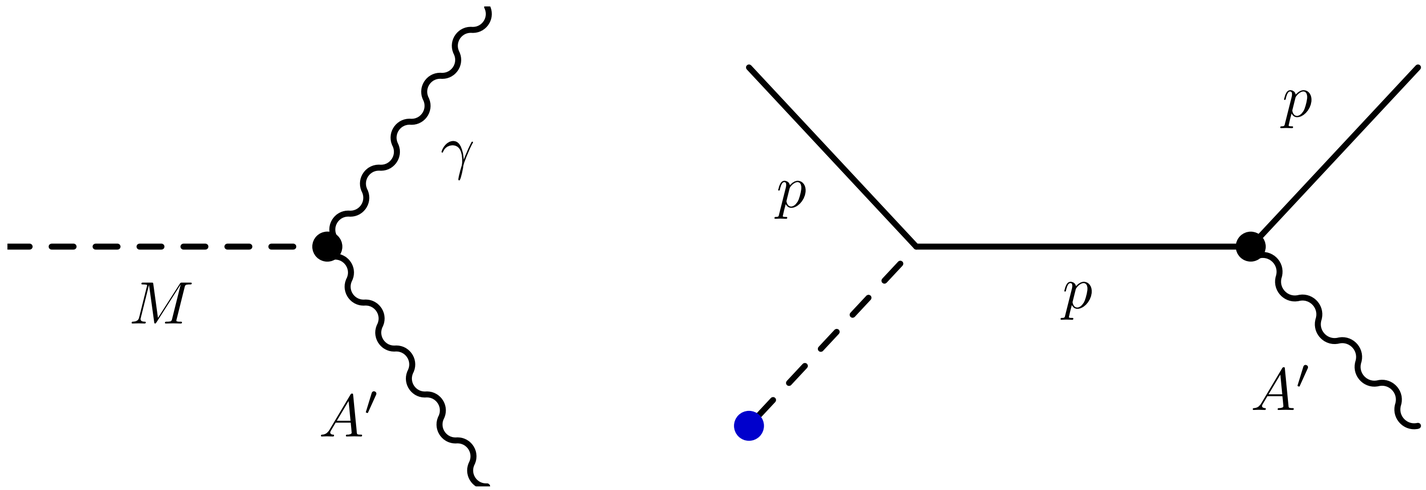


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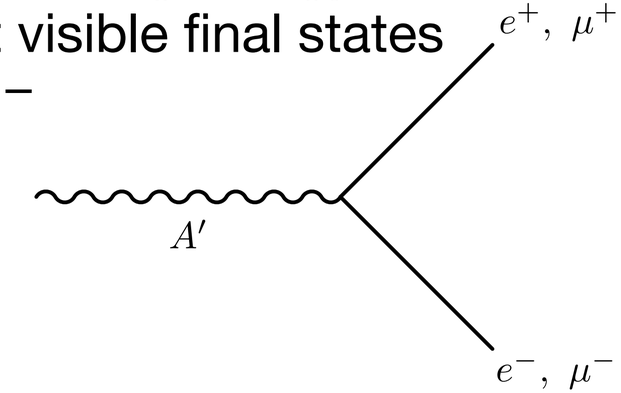
- DUNE Near Detector: 120 GeV proton beam hits fixed target
  - Production and decay of neutral mesons $\pi^0$, $\eta \to \gamma A'$
  - Bremsstrahlung process: $pp \to ppA'$
- Search for missing energy or reconstruct visible final states $e^+e^-$, $\mu^+\mu^-$



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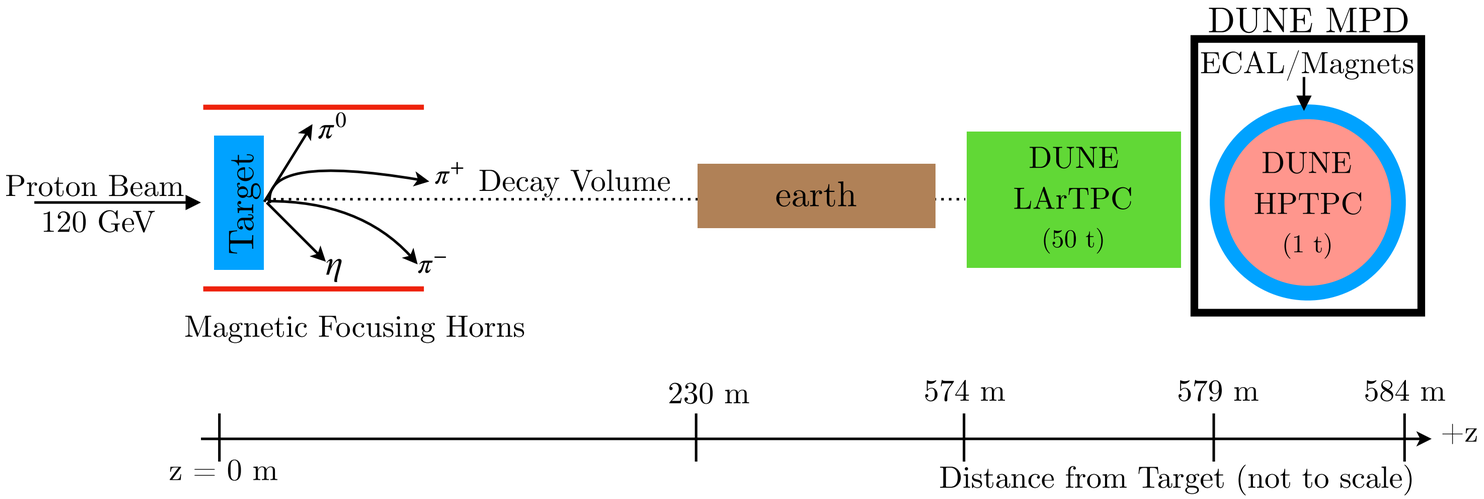


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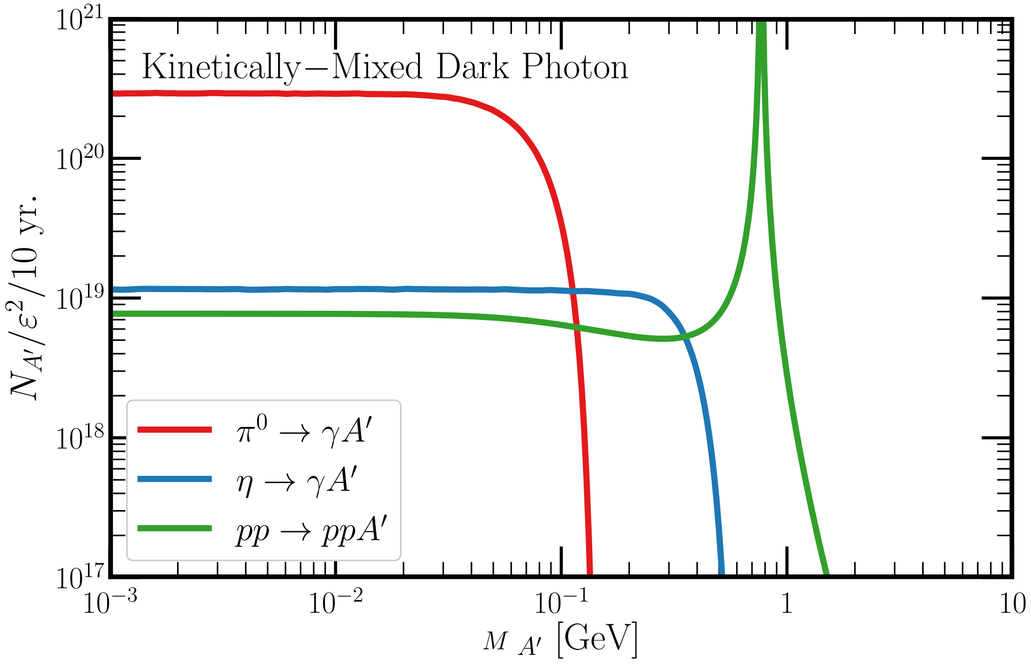

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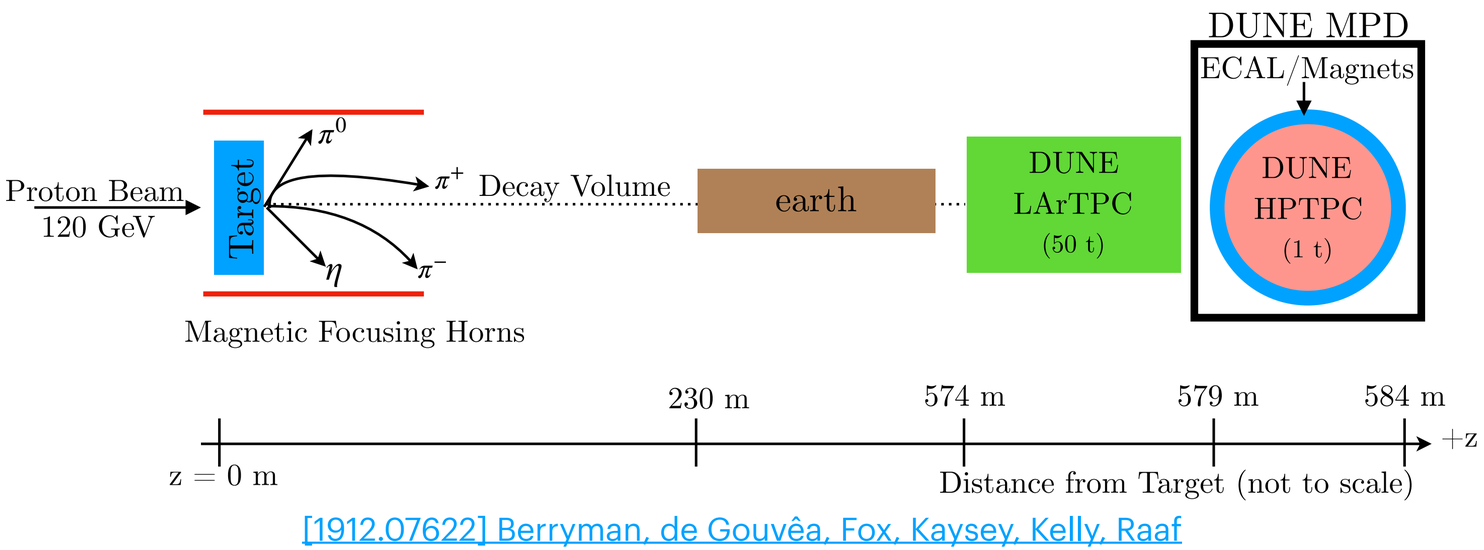


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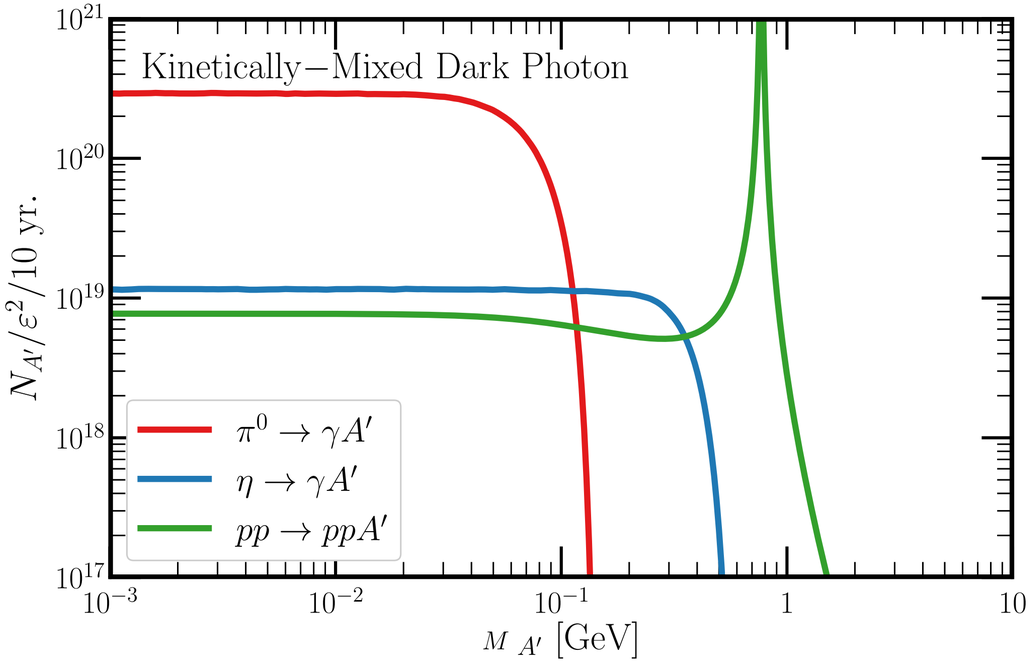


- Small solid angle of detector

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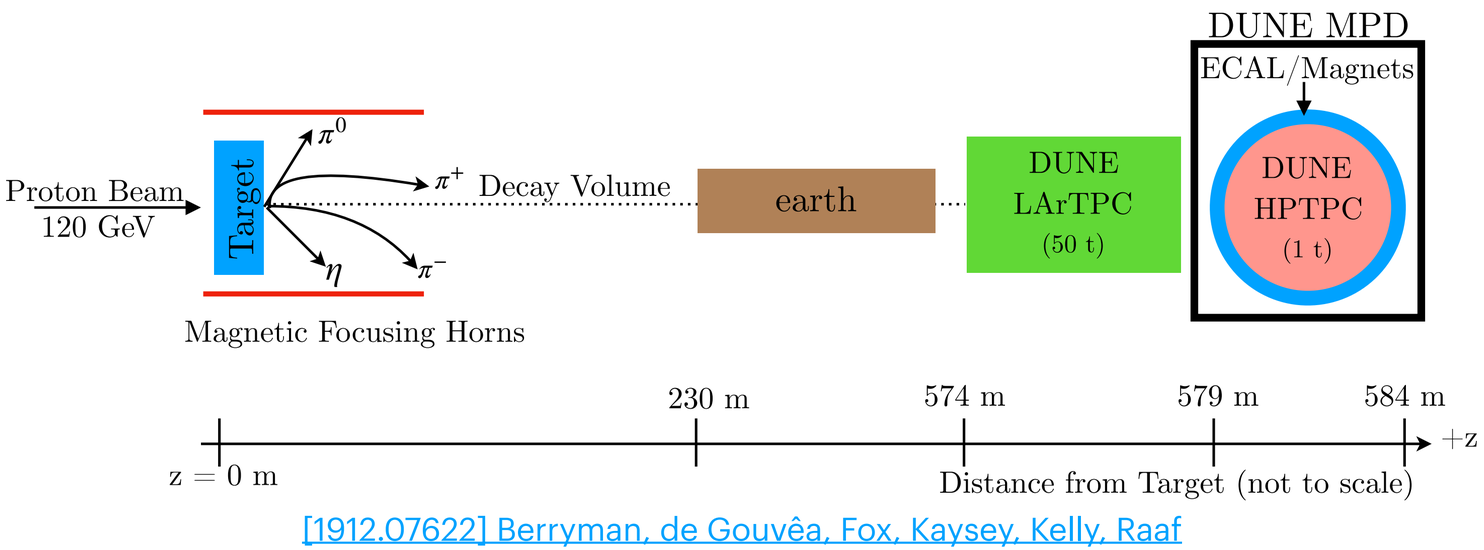


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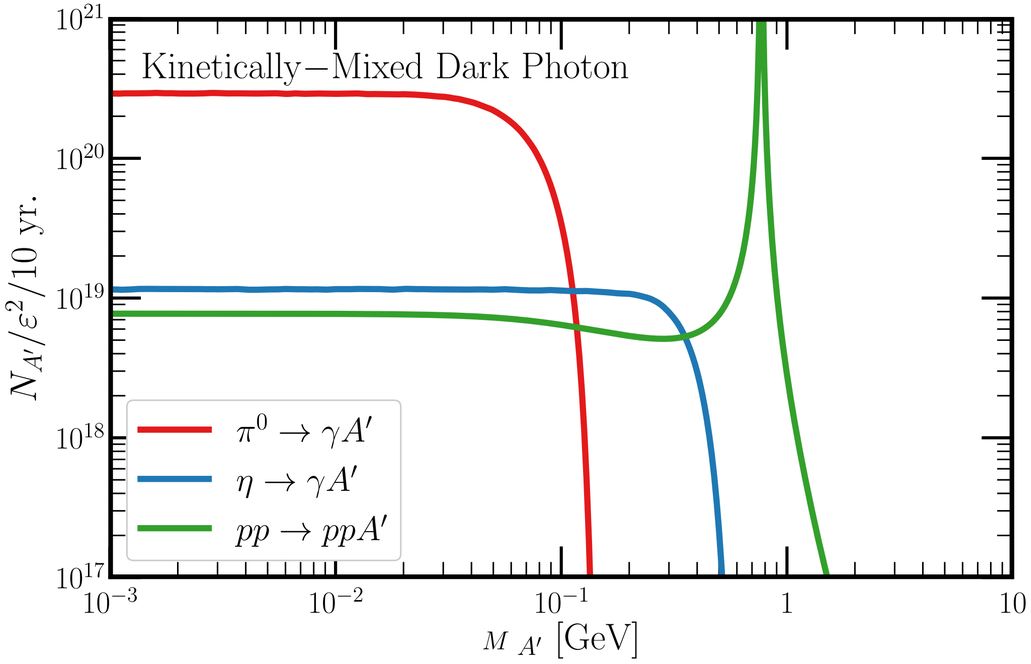


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- $A'$ must survive for $\sim 500$ m, then decay within $5$ m

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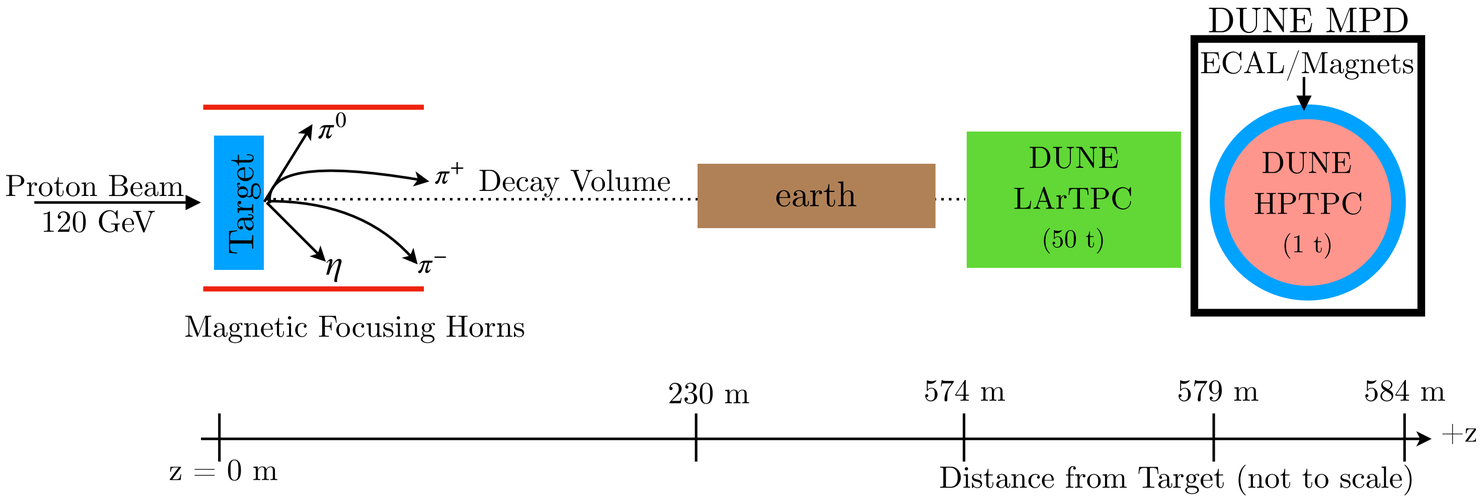


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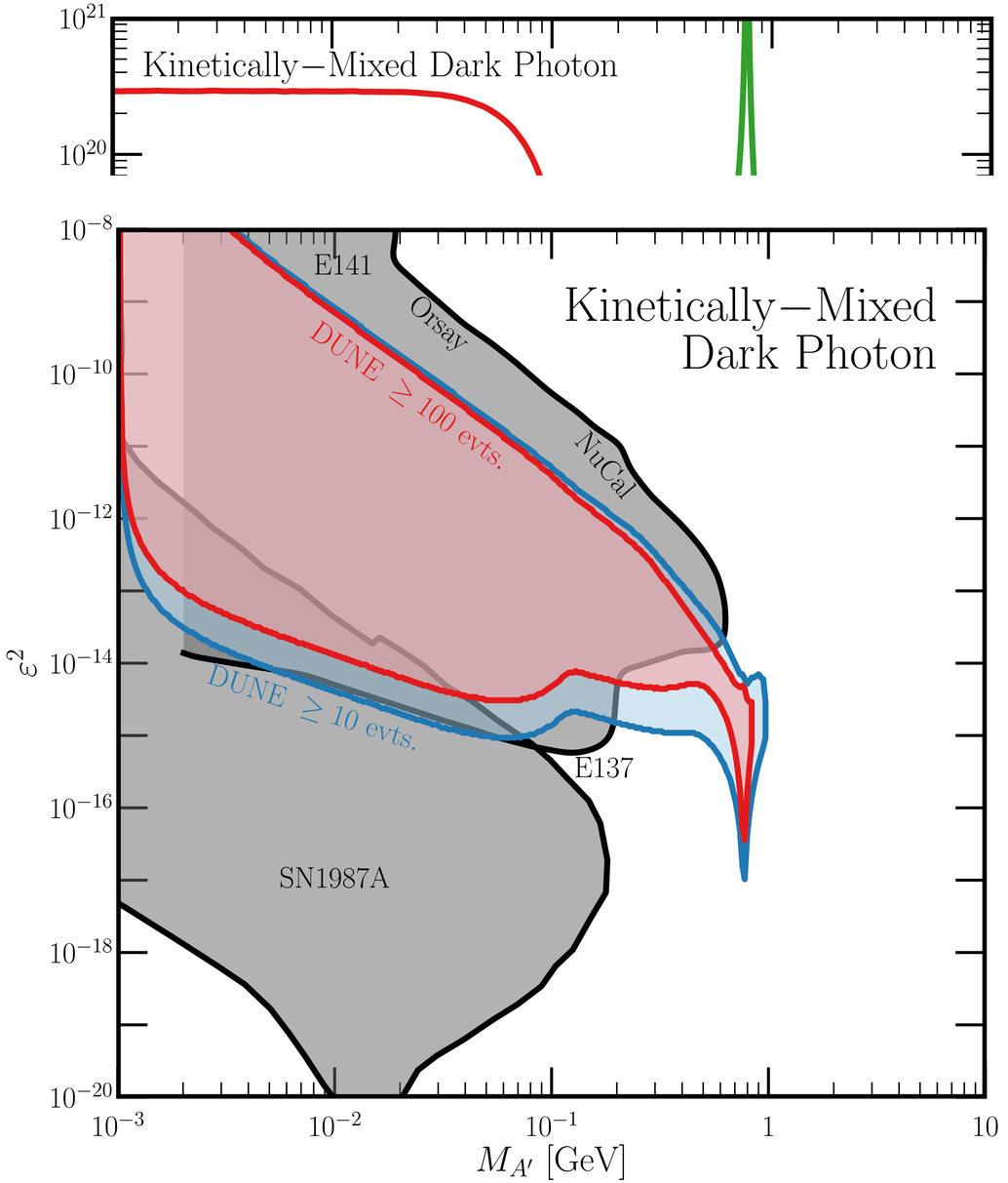


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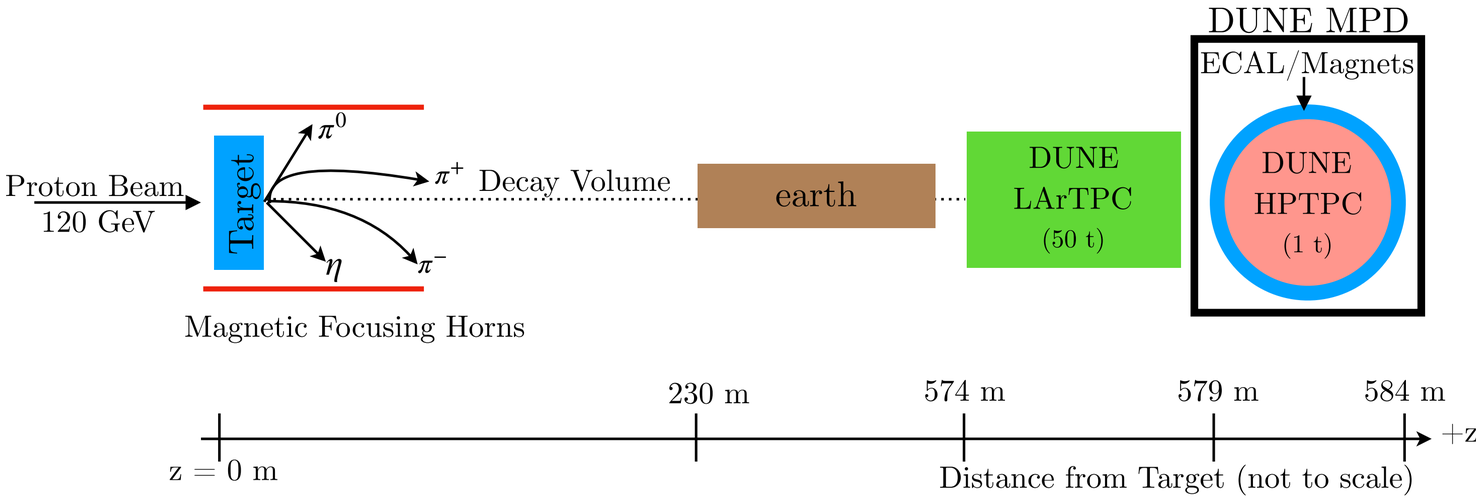


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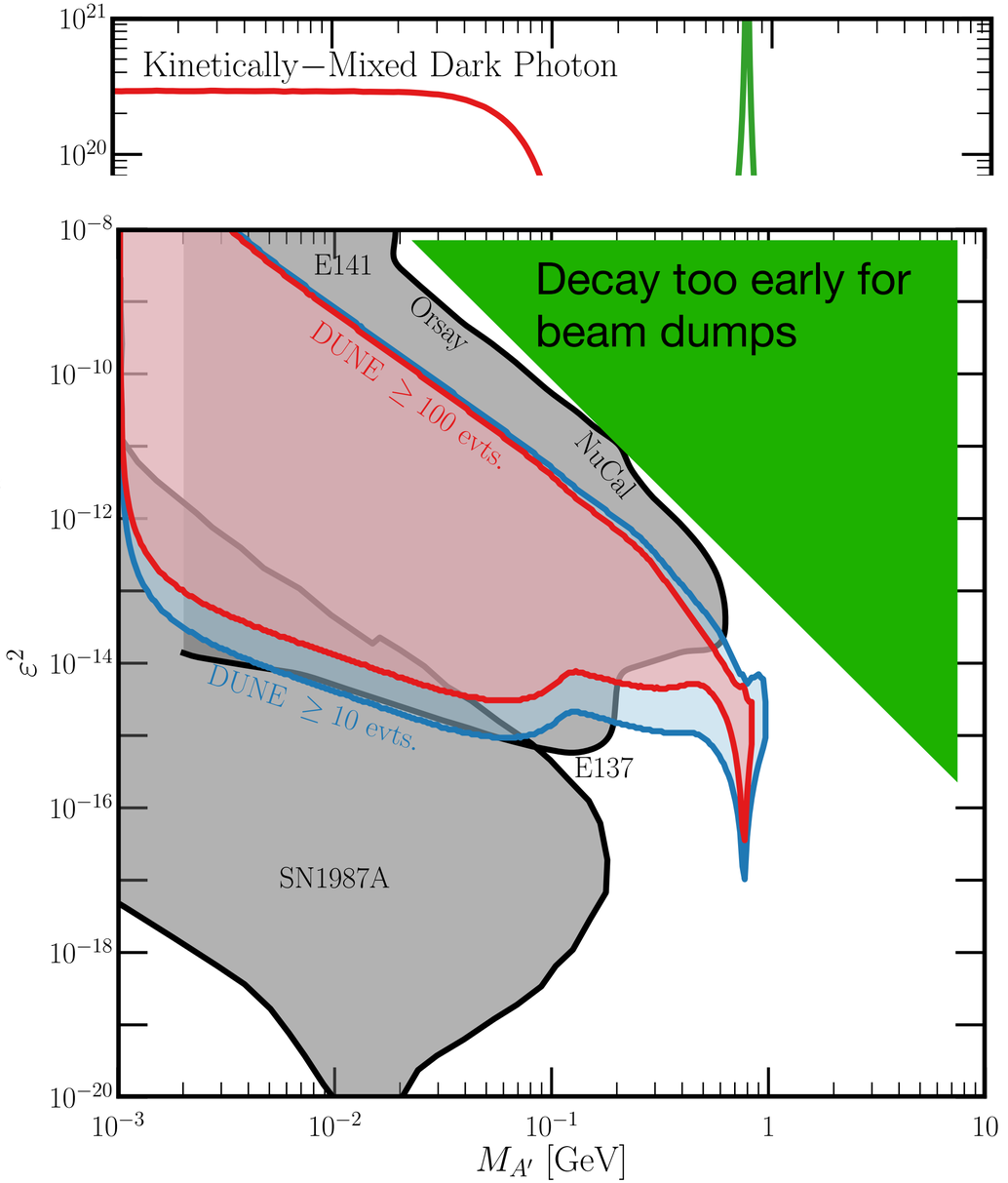
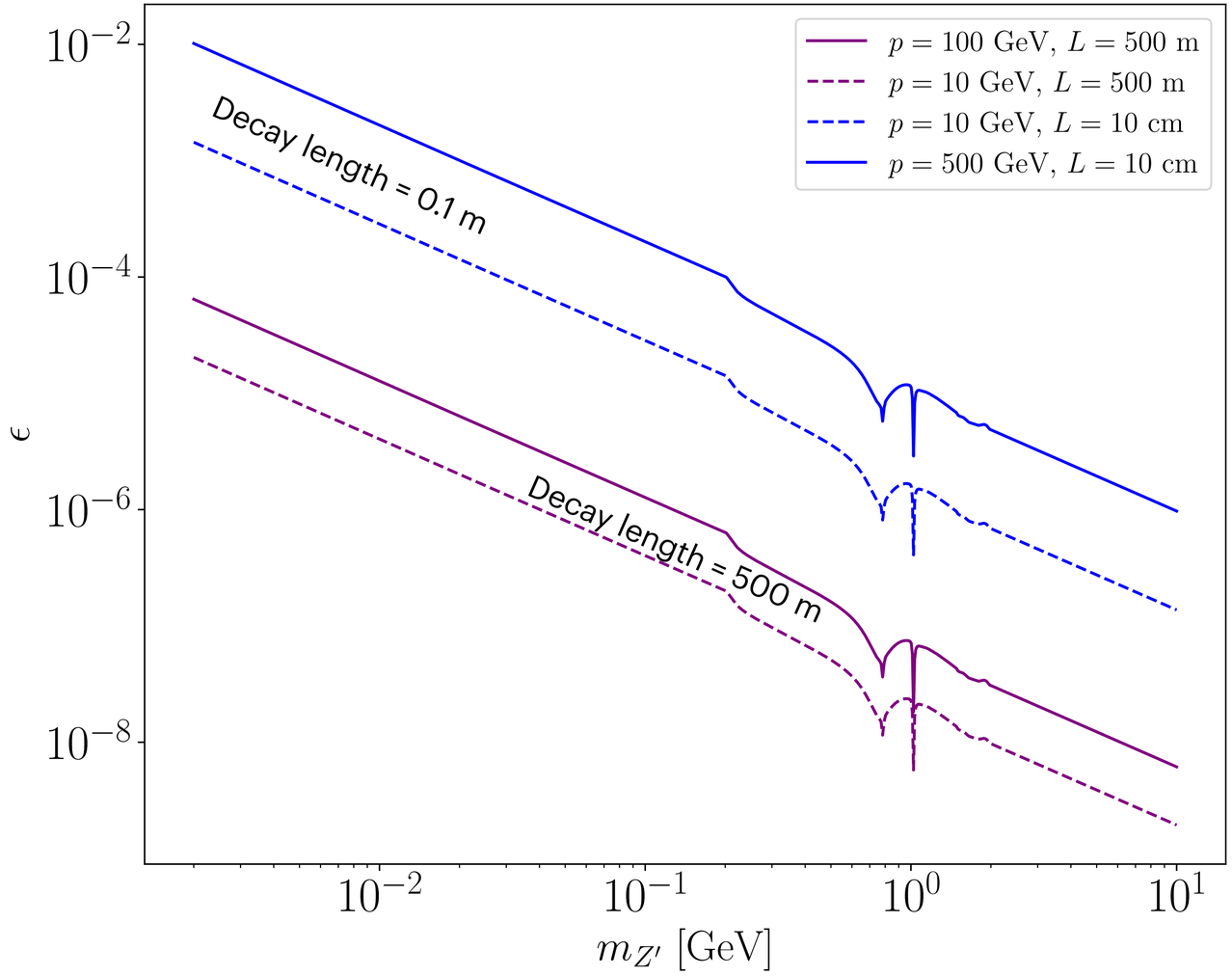


# Connecting parameter space to detector geometry

- Ceiling of sensitivity from required survival length of produced dark photons




https://athompson-git.github.io/experiments.html

# Connecting parameter space to detector geometry

- Ceiling of sensitivity from required survival length of produced dark photons
- Typical fixed target baseline:

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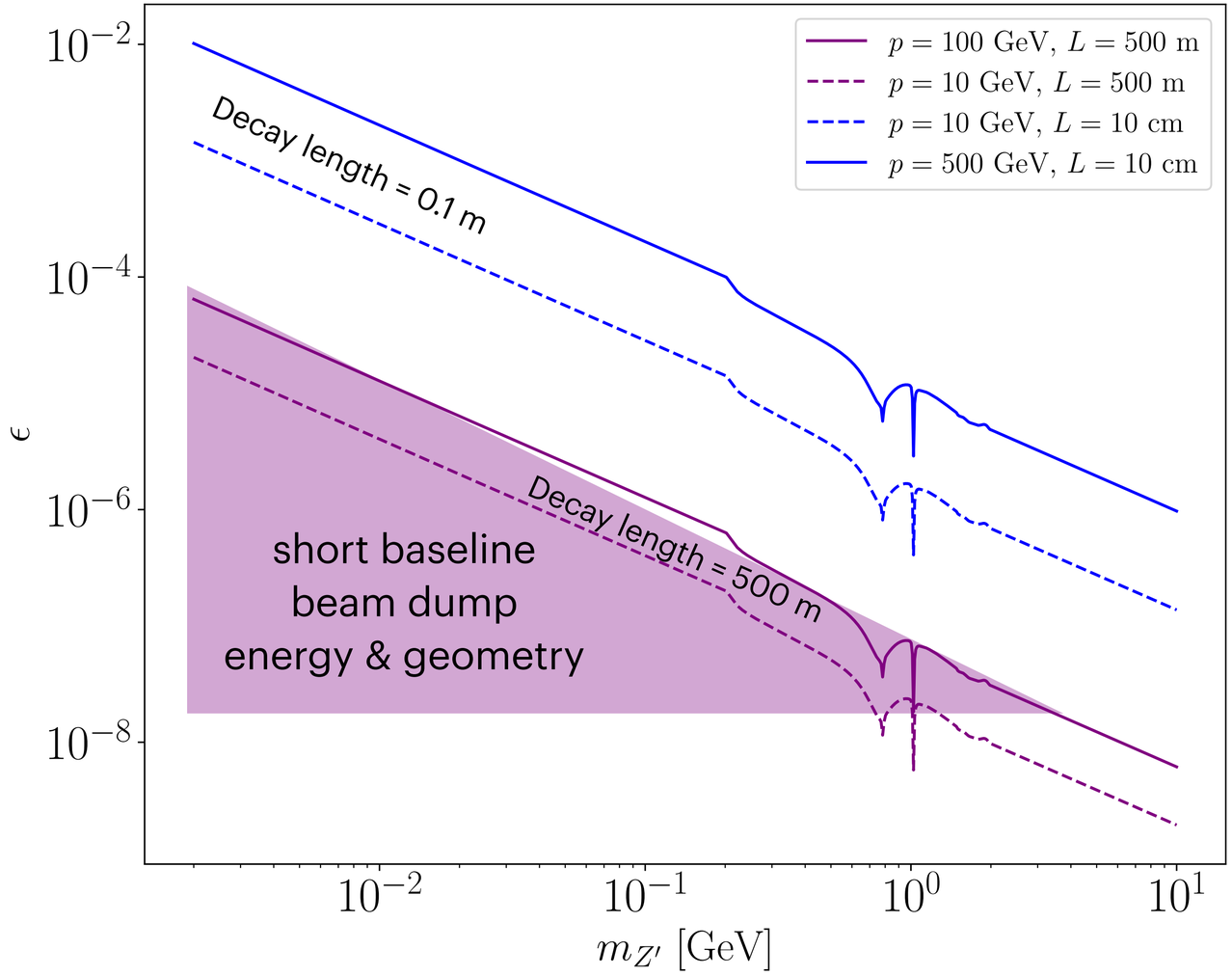


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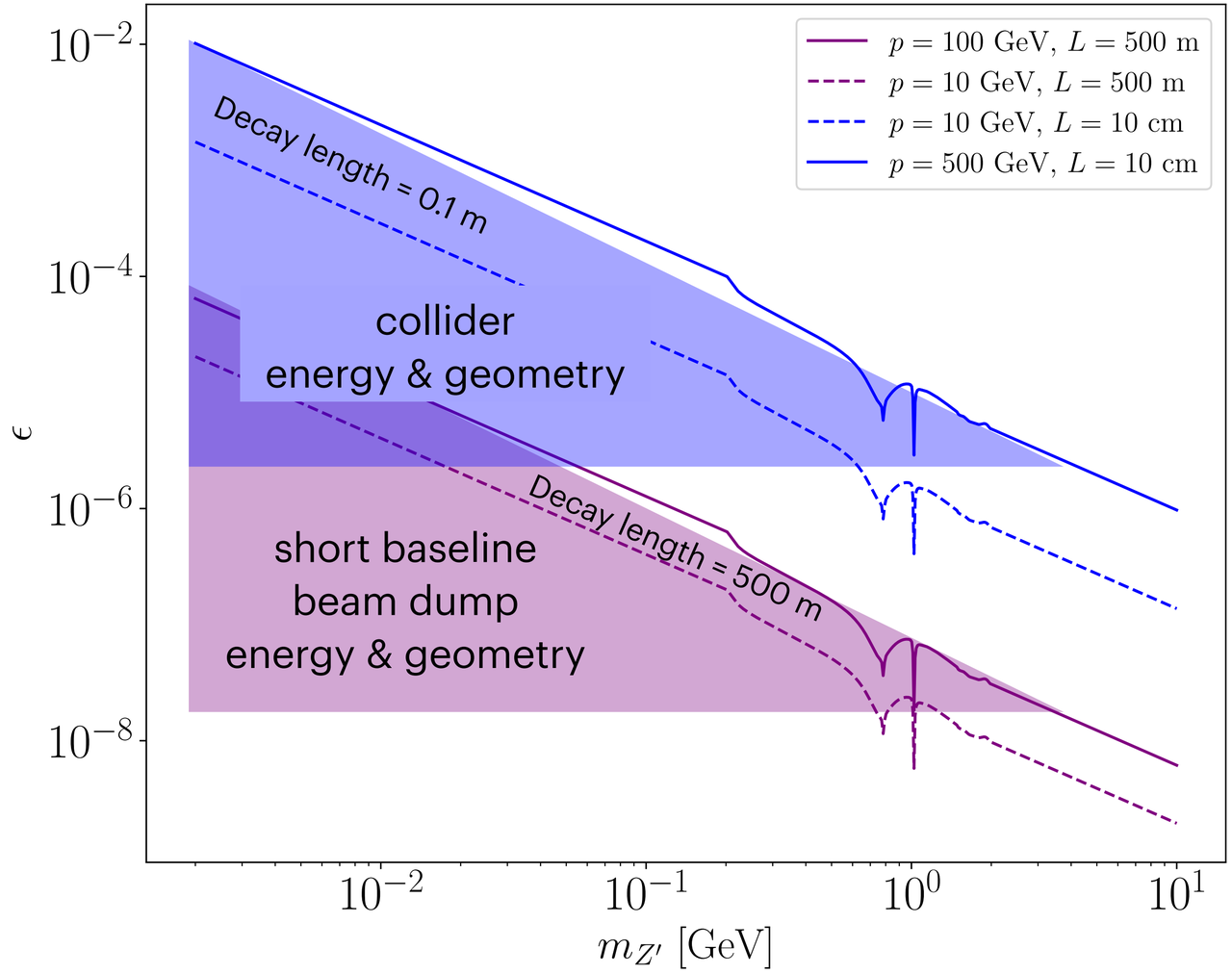
# Connecting parameter space to detector geometry

- Ceiling of sensitivity from required survival length of produced dark photons
- Typical fixed target baseline:
  $\sim 50 - 500$ m
- If the survival length is shortened to $\mathcal{O}(0.1$ m$)$, the ceiling is pushed higher
  - This can be done with collider detectors

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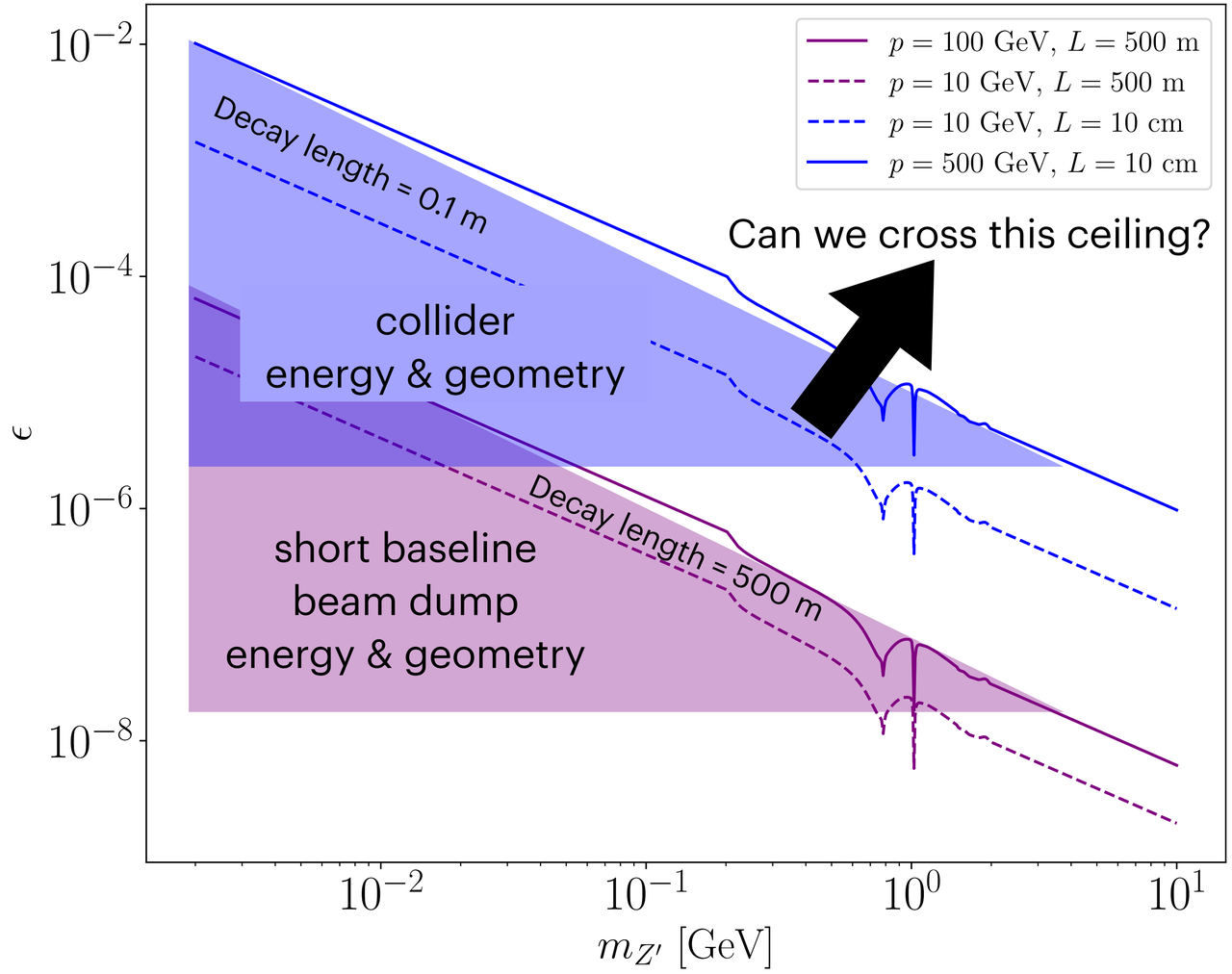
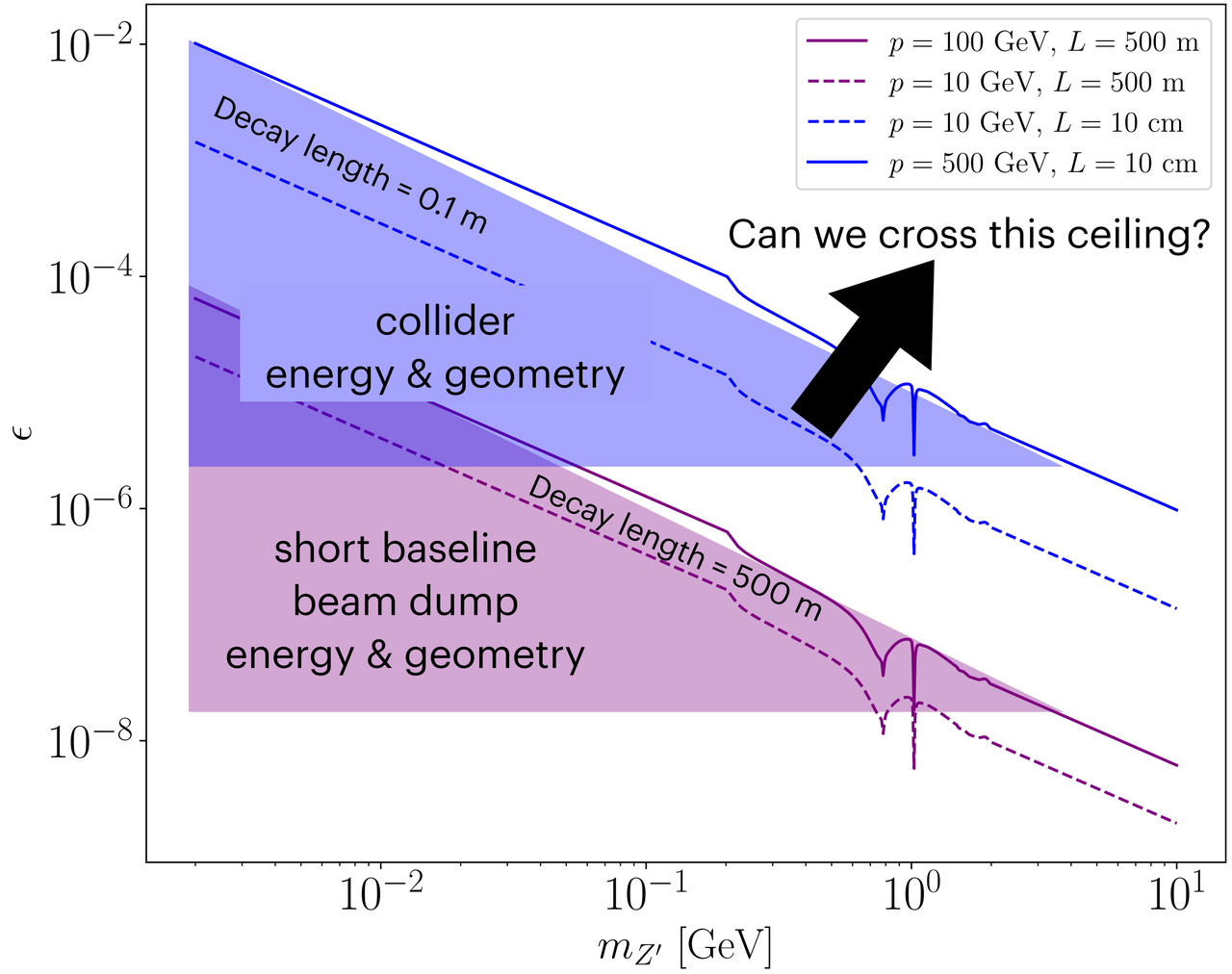
# Connecting parameter space to detector geometry

- Remove requirement of survival length with low backgrounds?



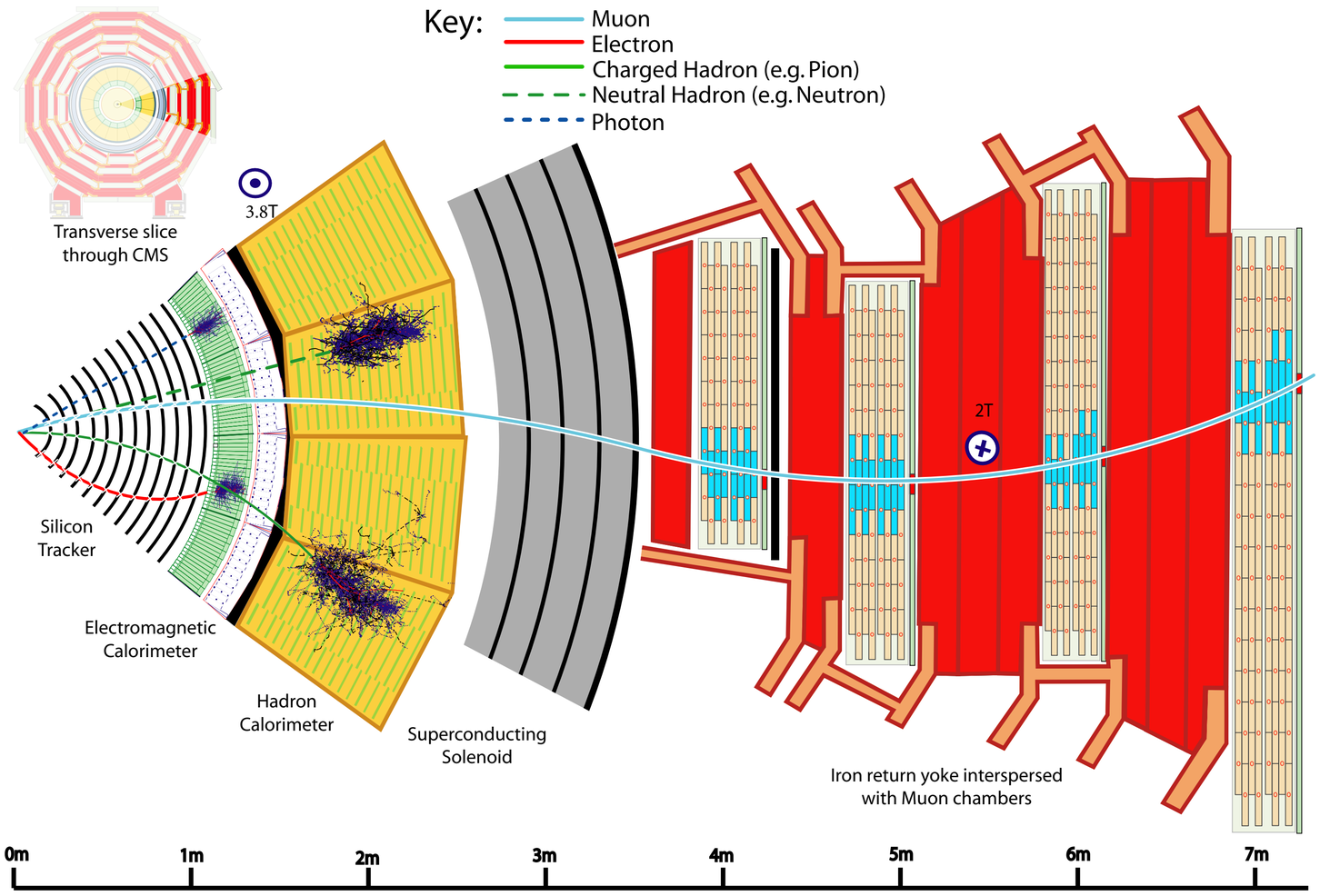
# Connecting parameter space to detector geometry

- Remove requirement of survival length with low backgrounds?
- LHC can do this by producing dark photons in the detector itself! Will show schematically



# LHC as Source and Detector

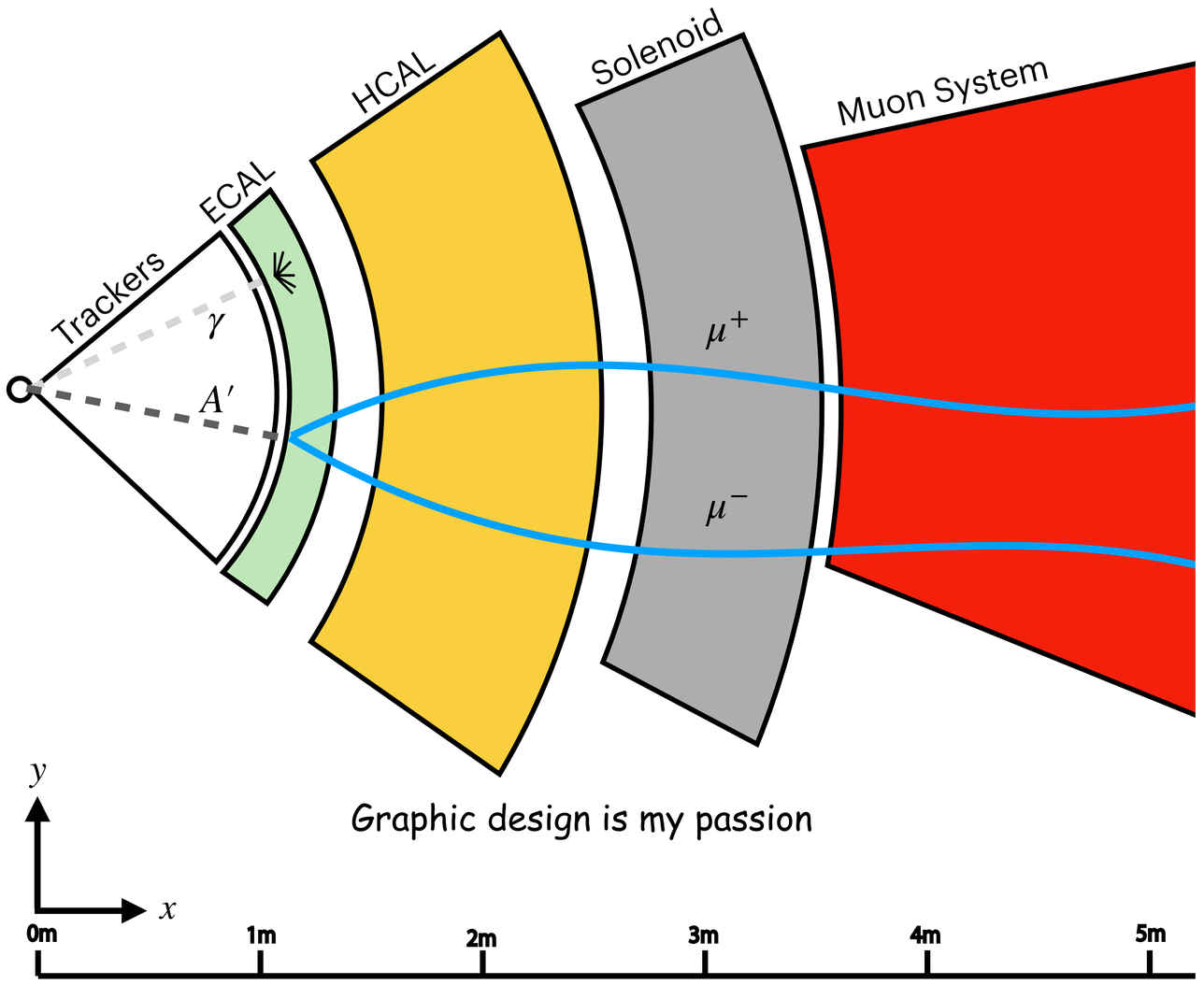
- Large solid angle of detector: only forward region escapes detector
  - $\sim 1/3 - 2/3$ events reach endcap and barrel of CMS detector
- Shorter survival length than DUNE, FASER




[1706.04965] CMS Collaboration

# Schematic: $\eta$ Meson Decay

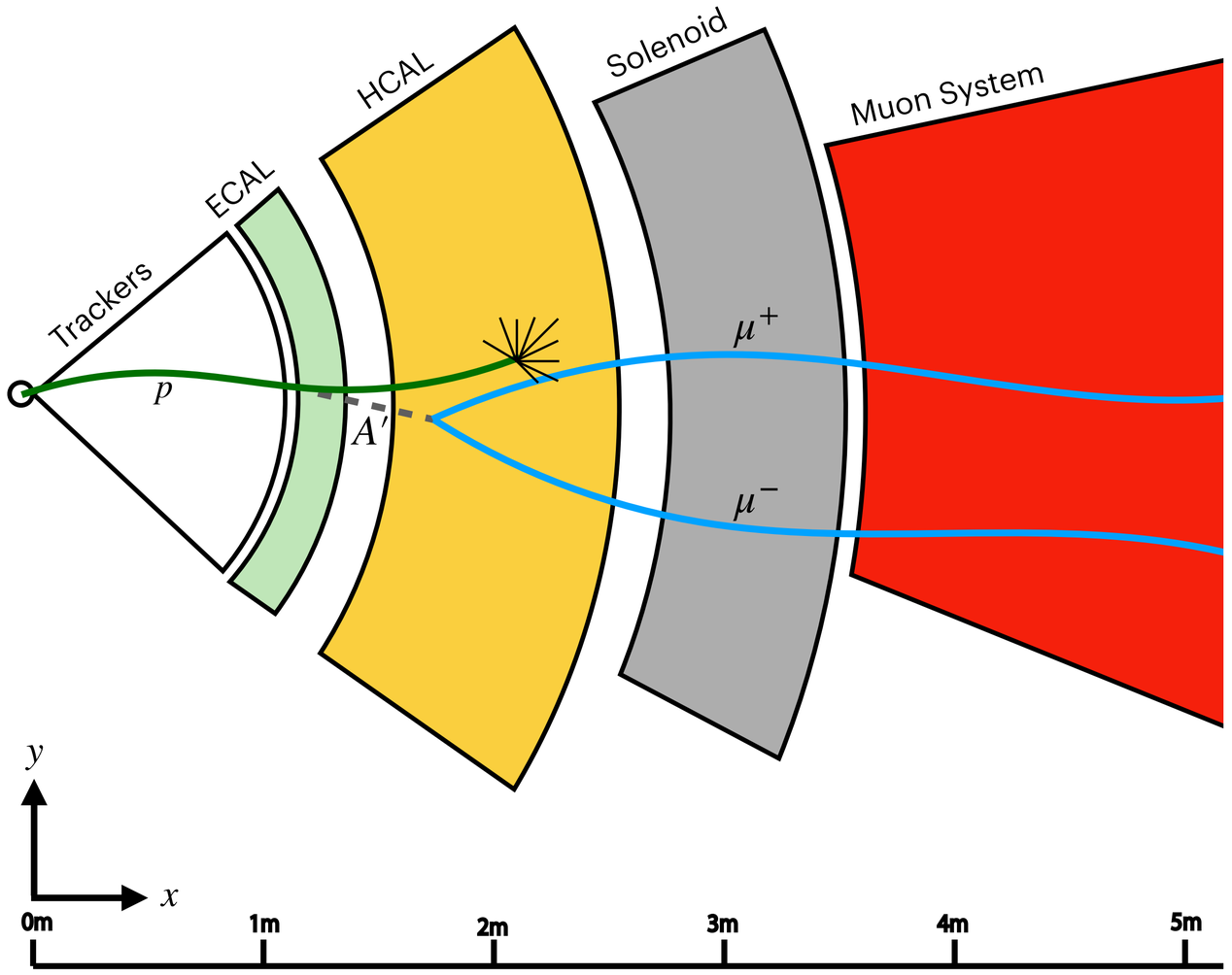
- $\eta$ produced at primary interaction point, promptly decays to $\gamma A'$
- $A'$ decays to $\mu^+\mu^-$ after $\gtrsim 0.7$ m
- Dimuons observed in muon system with large displaced vertex
- $m_{\mu\mu} = m_{A'}$ and $m_{\gamma\mu\mu} = m_{\eta}$




based on [1706.04965] CMS Collaboration

# Schematic: proton bremsstrahlung

- proton produced at primary interaction point
  - Brems $A'$ in ECAL
- $A'$ decays to $\mu^+\mu^-$, can be prompt
- Dimuons observed in muon system with large displaced vertex
- $m_{\mu\mu} = m_{A'}$, can correlate HCAL observation with displaced dimuons

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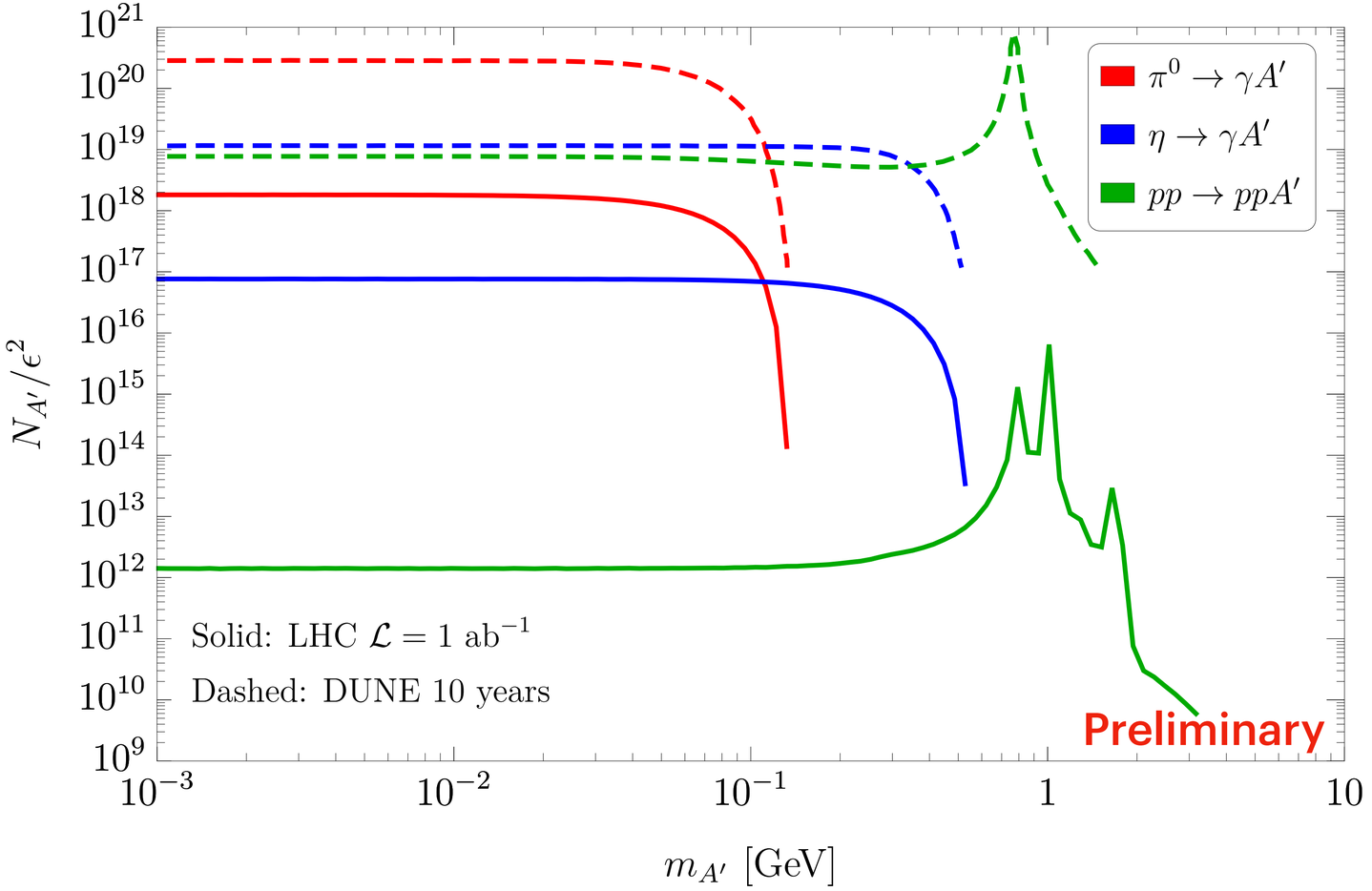
# LHC as Source and Detector

- LHC numbers obtained using Pythia, cross-checked with EPOS LHC for low energy mesons, protons




[2409.09123] Foroughi-Abari, Reimitz, Ritz

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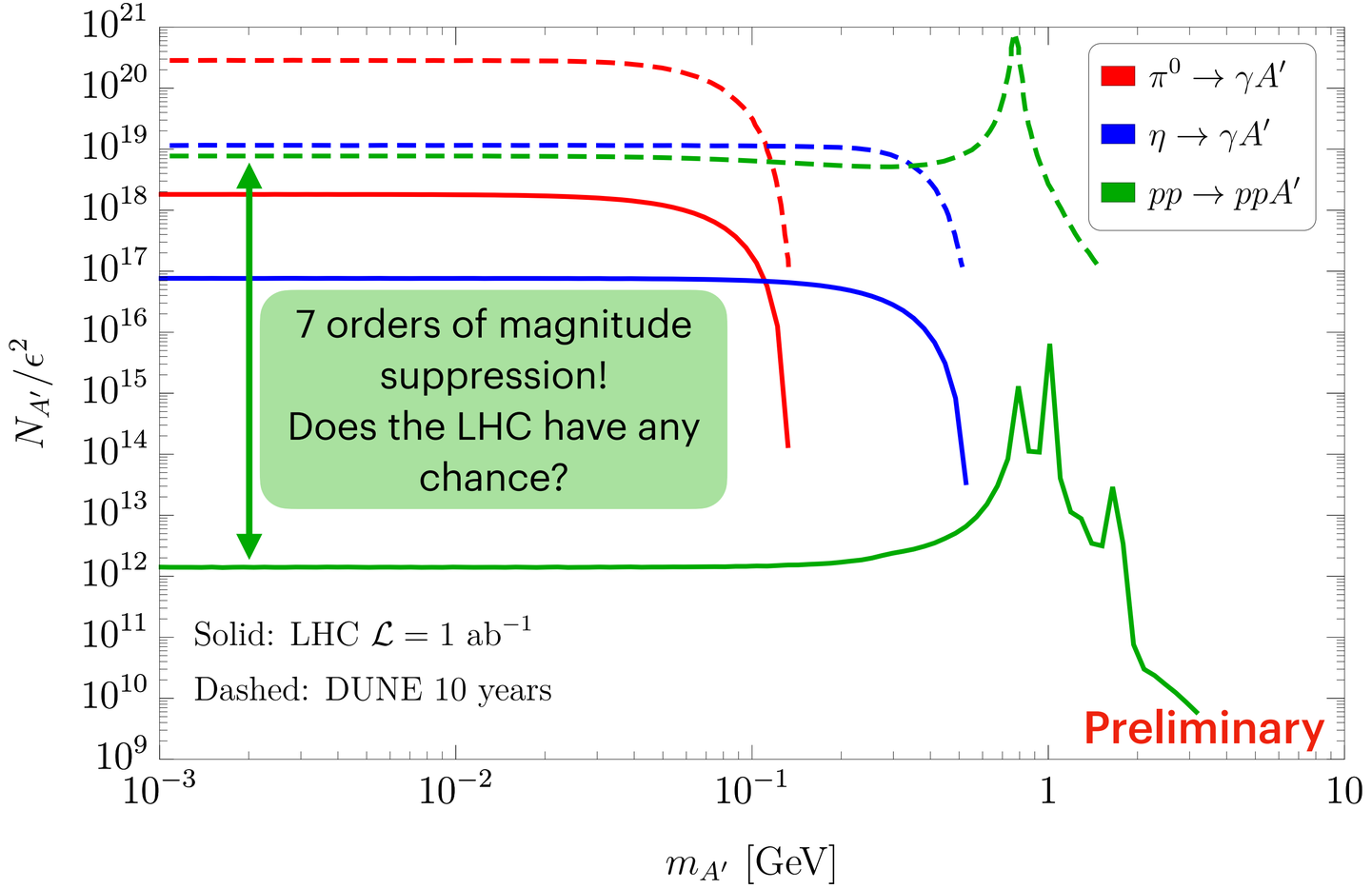


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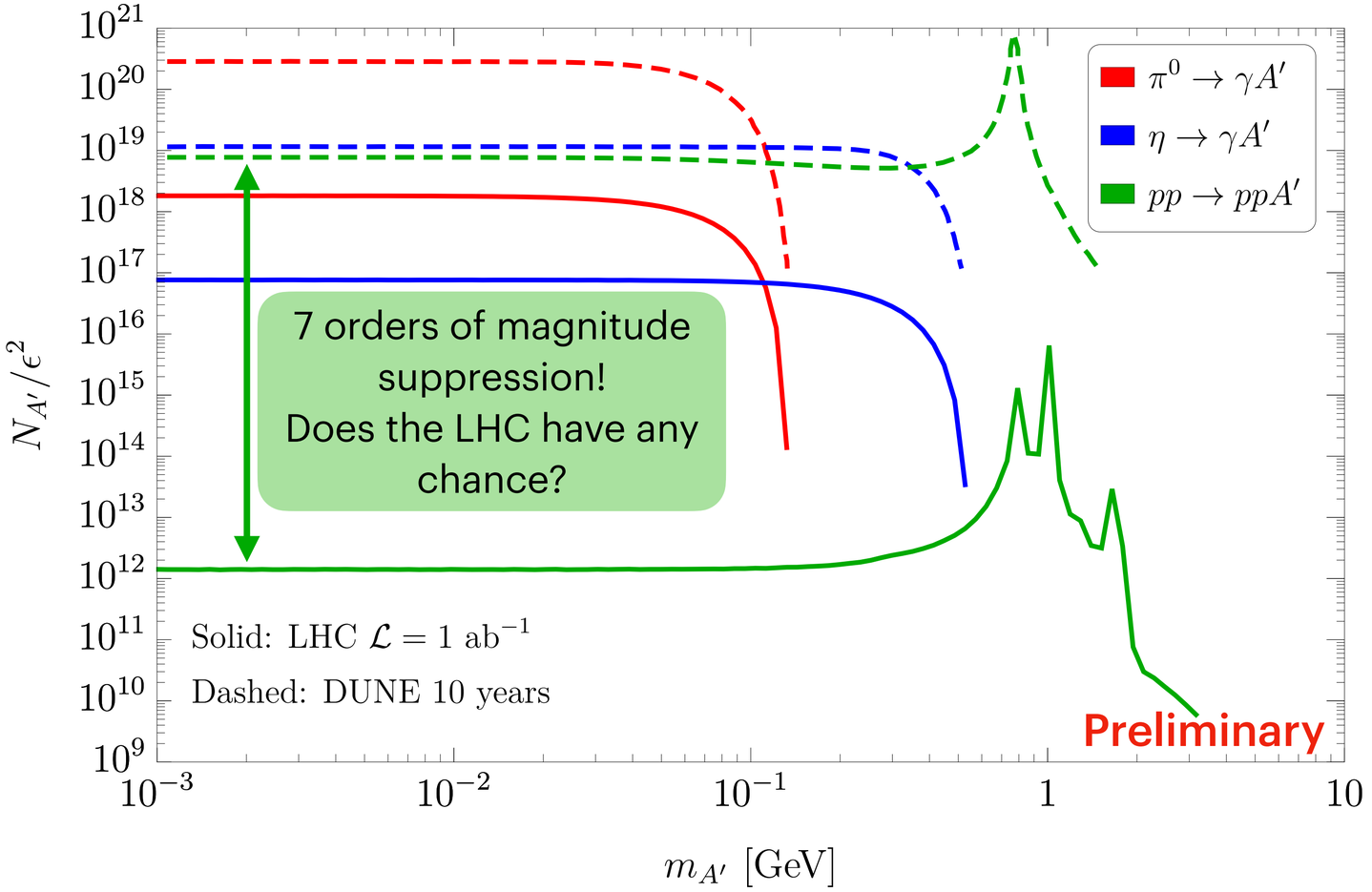


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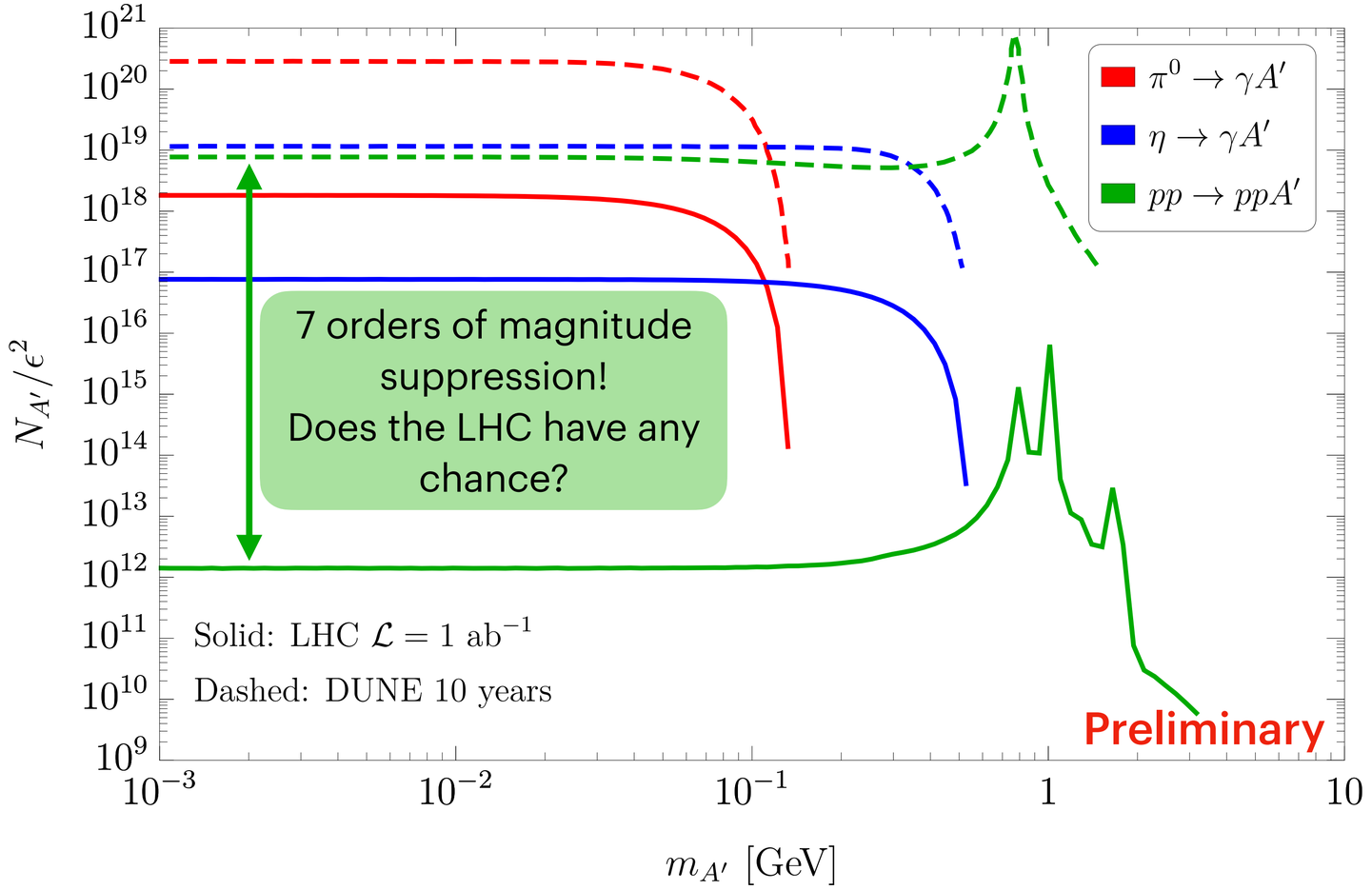
  - Another channel: direct production via boosted Drell-Yan

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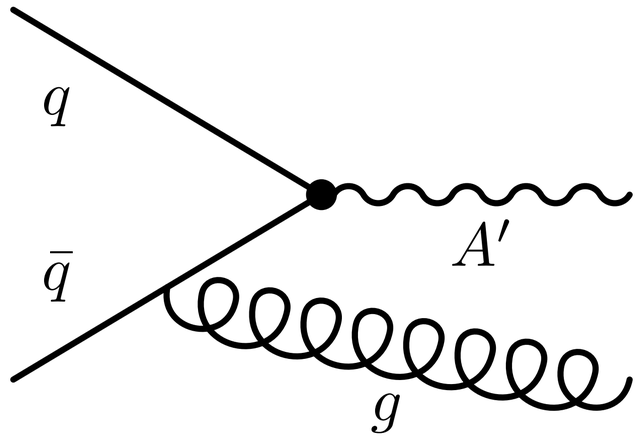
# Directly produced $A'$ at LHC

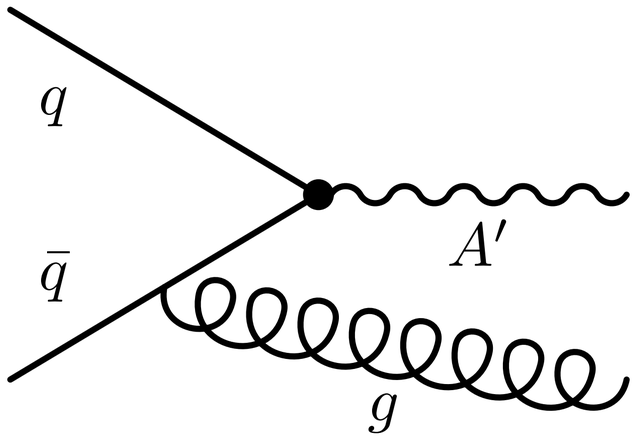
- Can we directly produce lots of $A'$ via associated production?



# Directly produced $A'$ at LHC

- Can we directly produce lots of $A'$ via associated production?
- Resonance/bump hunt searches for dimuon final states at the LHC explored
  - $m_{A'} > 10\ \mathrm{GeV}$, lighter masses unexplored at LHC

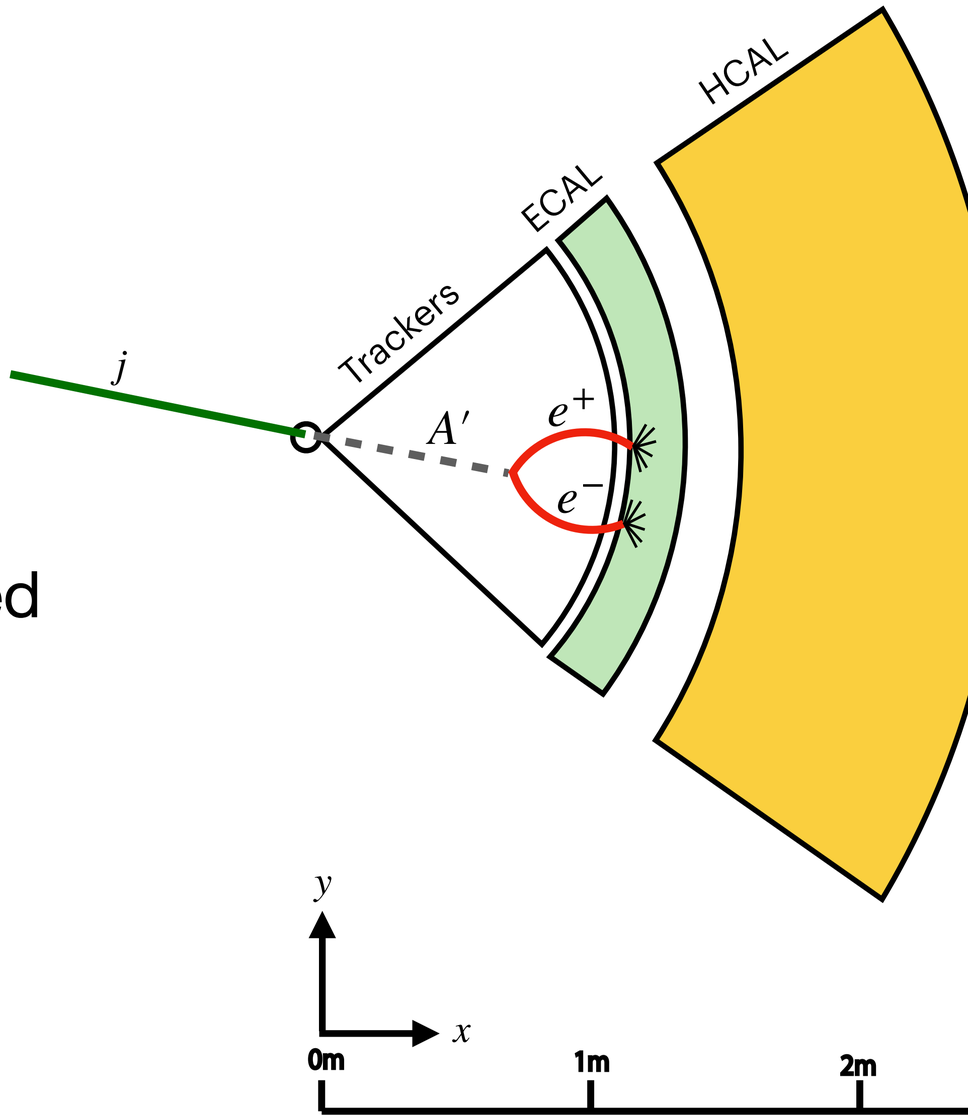
[1412.0018] Curtin, Essig, Gori, Shelton



# Schematic: direct production

- $A' + j$ produced at primary interaction point opposite each other
- $A'$ decays to $e^+e^-$ after $\gtrsim 0.1$ m

- Dielectrons observed in ECAL with large displaced vertex
- $m_{ee} = m_{A'}$ and jet correlated with $A'$
  - Can require sufficient $p_T^j$ and $p_T^e$ for triggering and boost for dielectron signal

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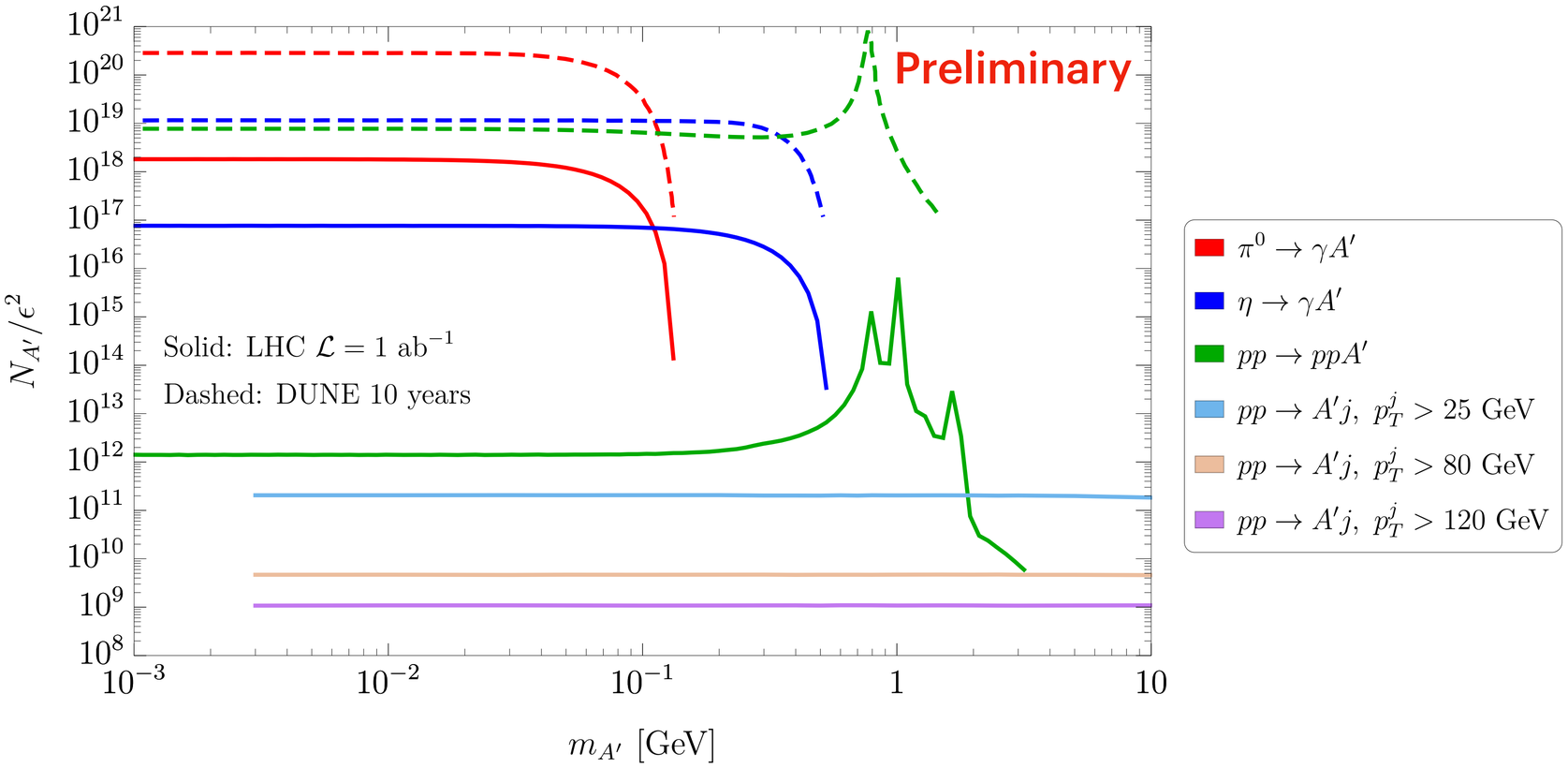

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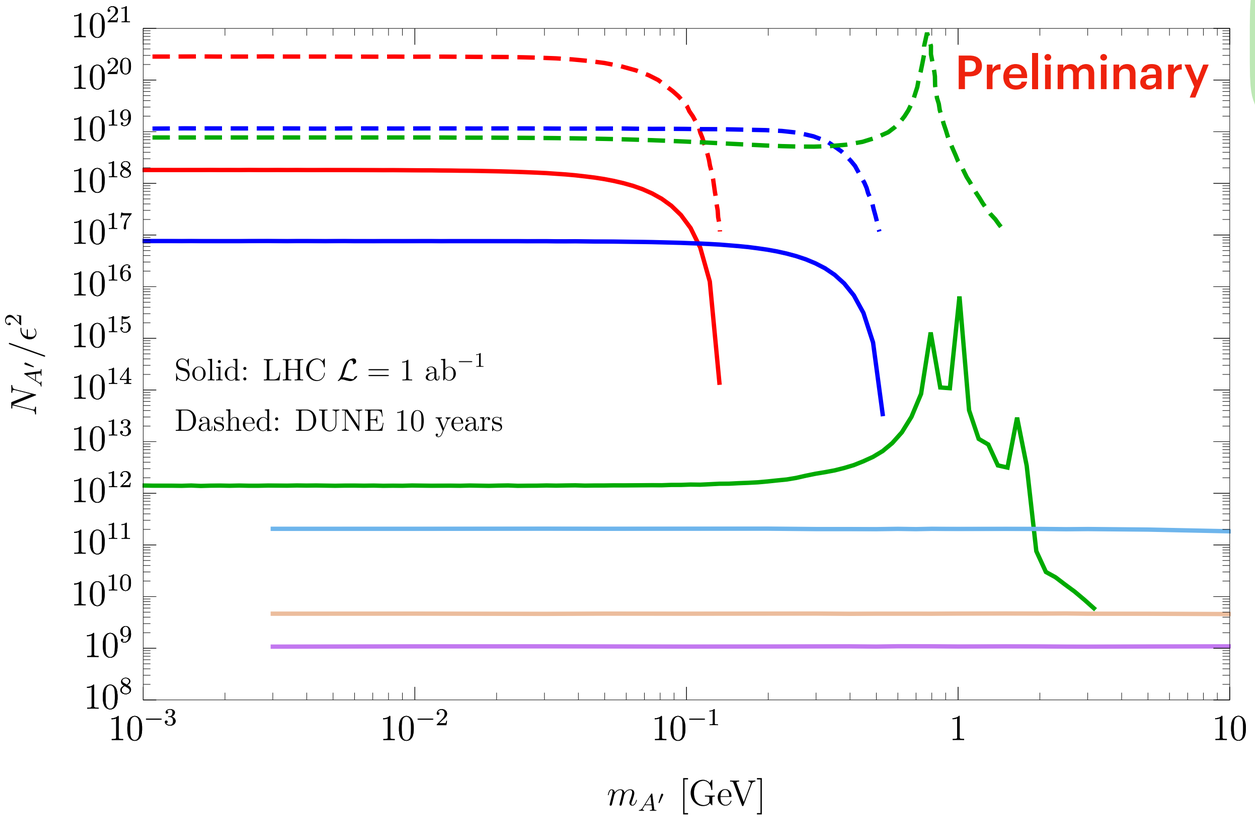
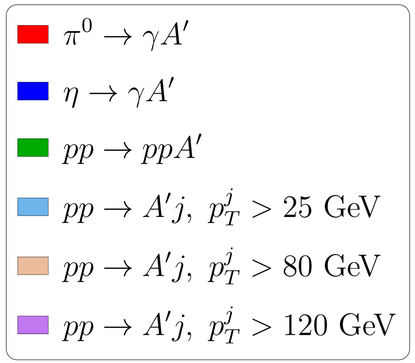



- LHC can produce MeV-GeV scale $A'$ with ISR jet
  - Estimates produced with MadGraph5



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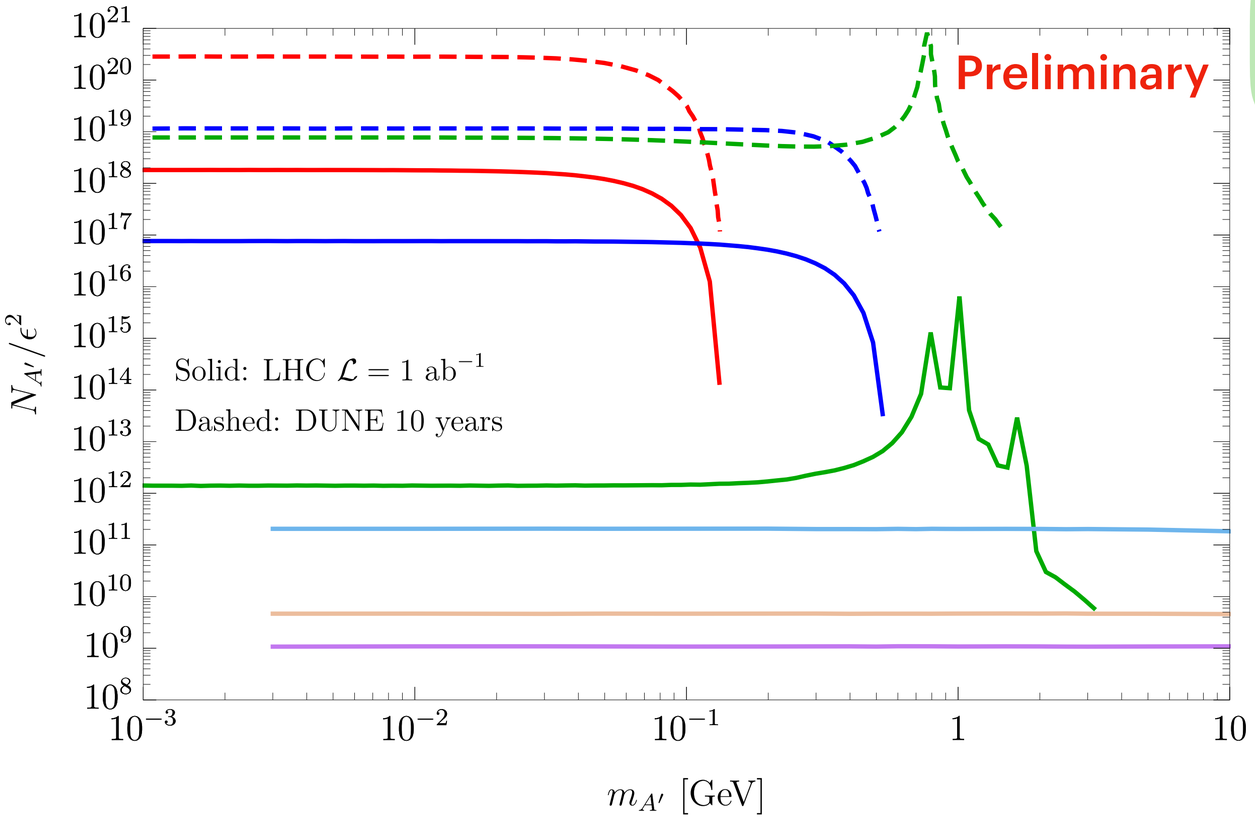
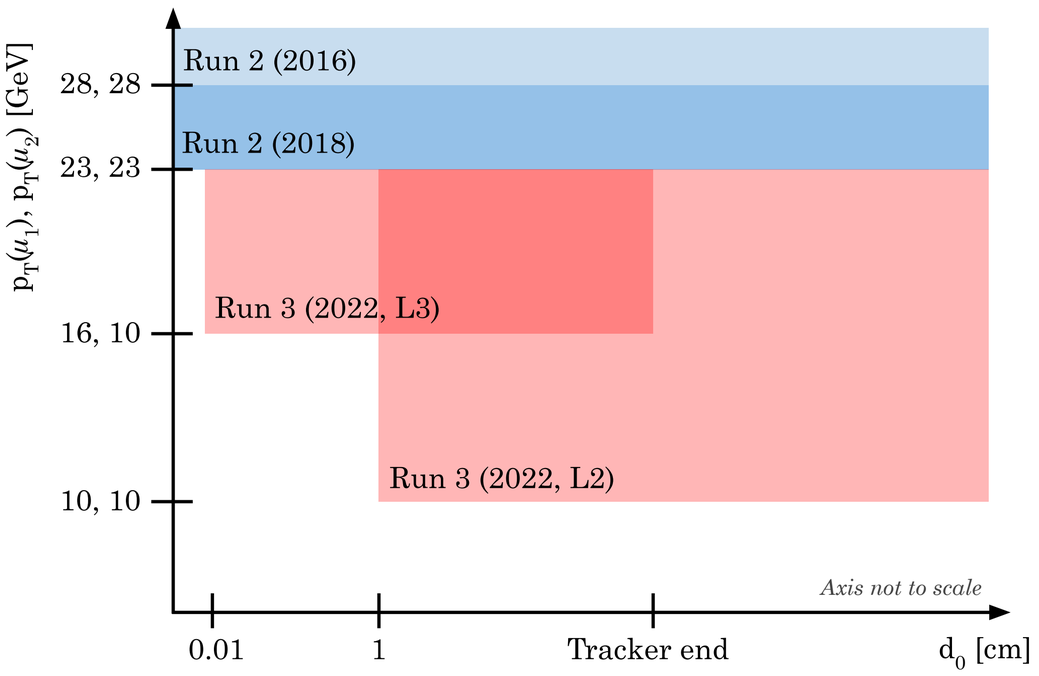



- LHC can produce MeV-GeV scale $A'$ with ISR jet
  - Estimates produced with MadGraph5
- Flux smaller than brem, meson production
  - Required energetic jet for correlation: $> 25$ GeV
  - Can produce boosted $e^+e^-$, visible leptonic channel for $m'_A < 2m_\mu$

# Projected Sensitivity

- What kind of sensitivity reach does the LHC have?




[2402.14491] CMS Collaboration

Note: $d_0$ is impact parameter, not transverse decay length $L_{xy}$

# Projected Sensitivity

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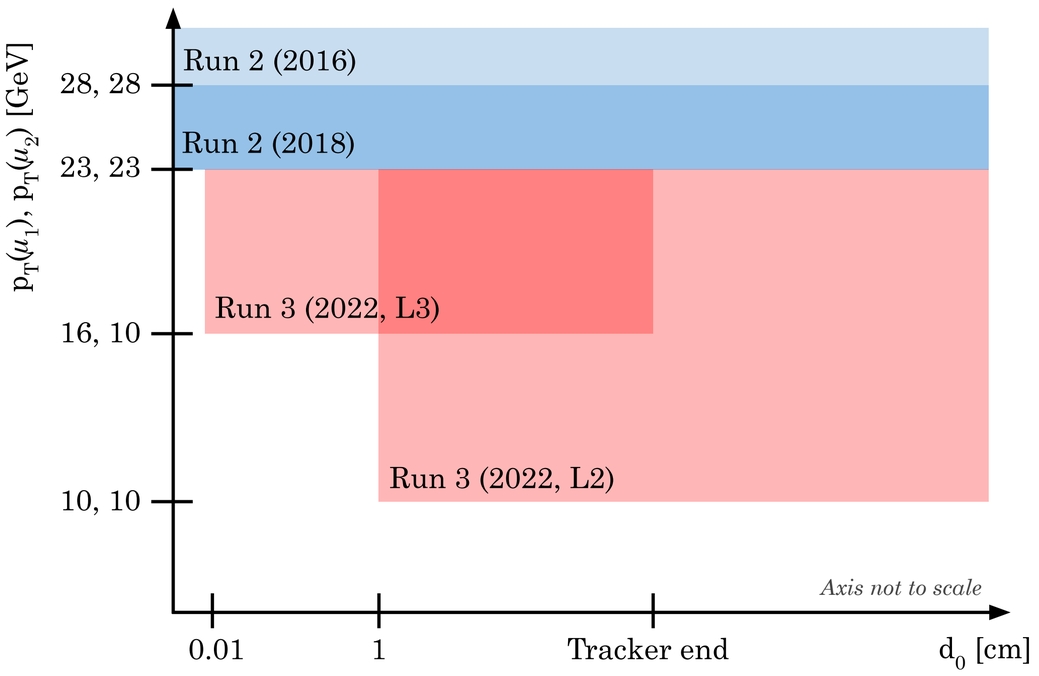
- Signal:
  - Dimuons produced without tracks (standalone) with $p_T^{\mu} > 10$ GeV
  - Dielectrons with displaced vertex and $p_T^{e} > 4$ GeV (parking data)

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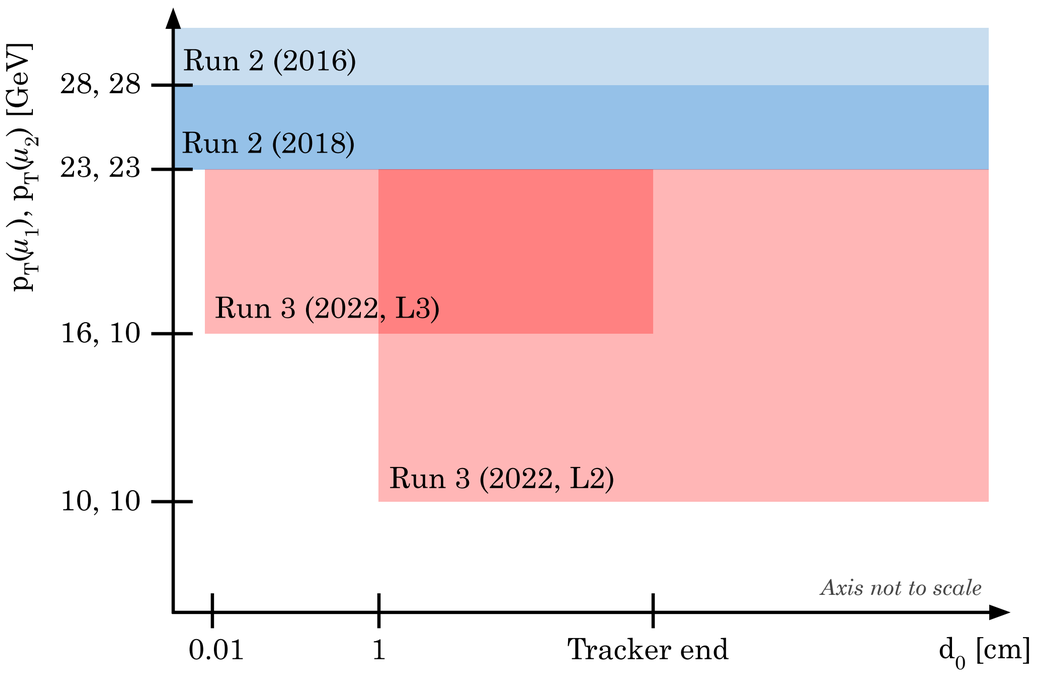
  - Dielectrons with displaced vertex and $p_T^e > 4\ \mathrm{GeV}$ (parking data)
- Different assumptions for each production mechanism:
  - Brem: $A'$ produced in ECAL, can decay promptly
  - Direct production: $A'$ must survive $\gtrsim 0.1\ \mathrm{m}$

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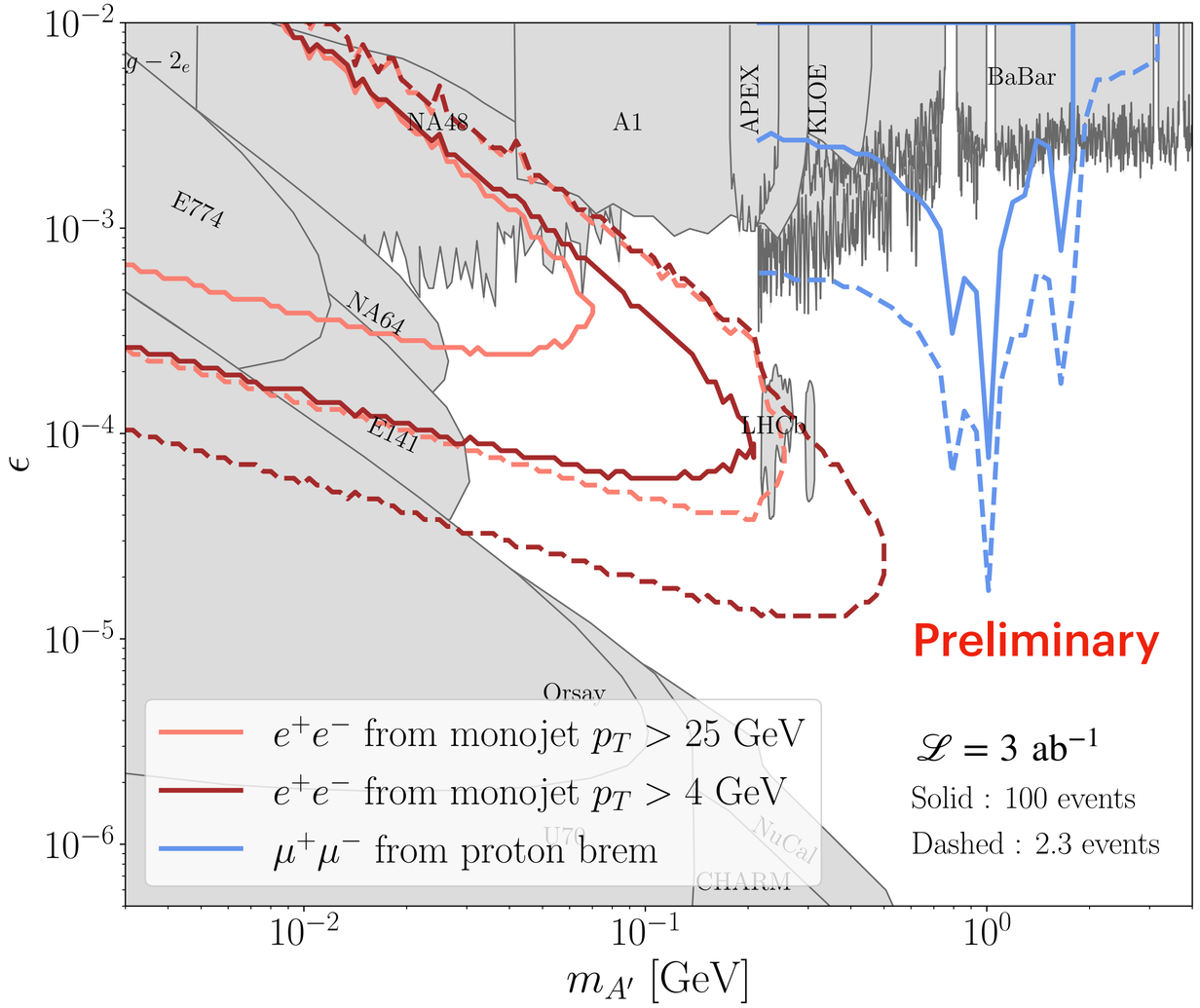

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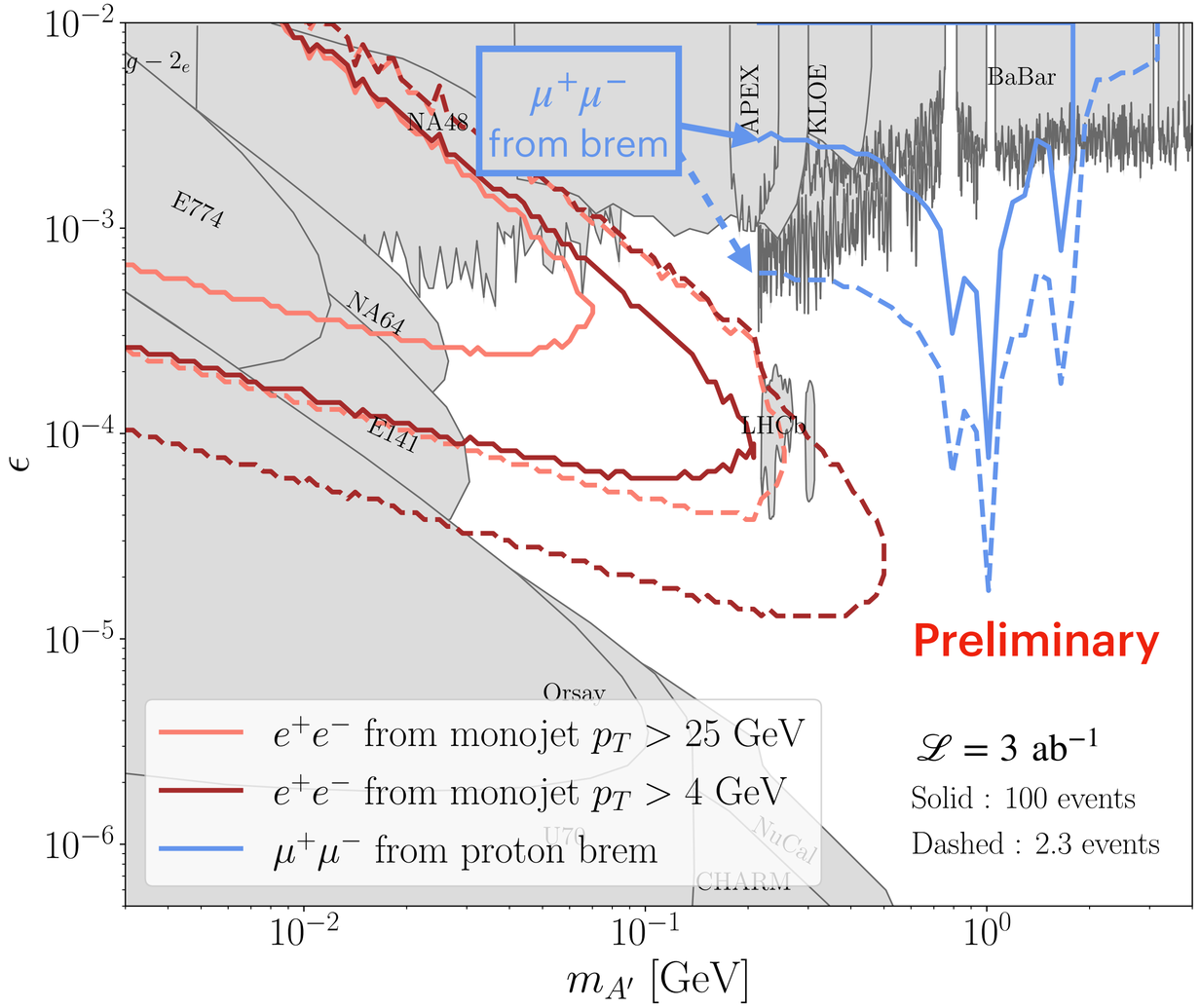
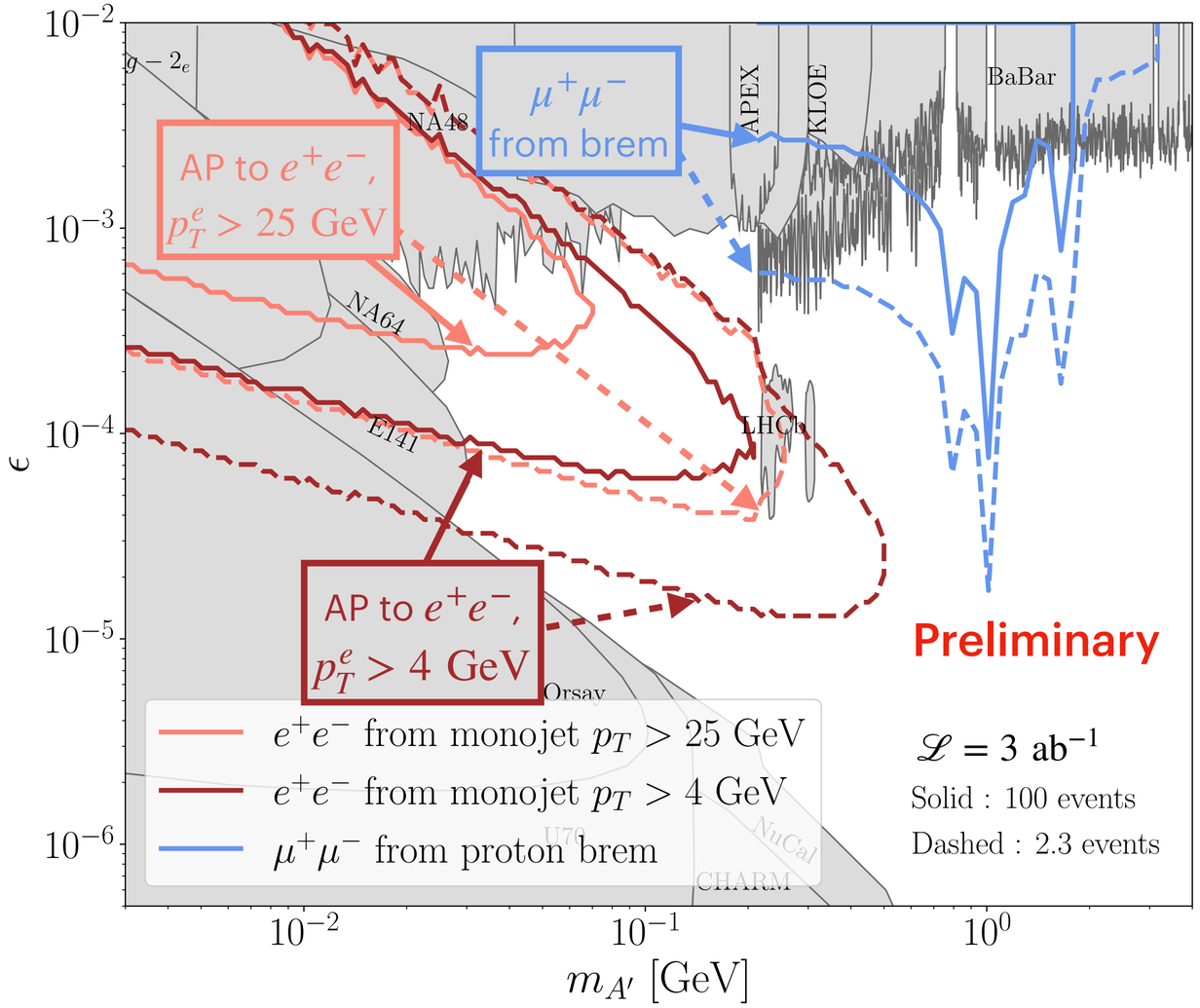


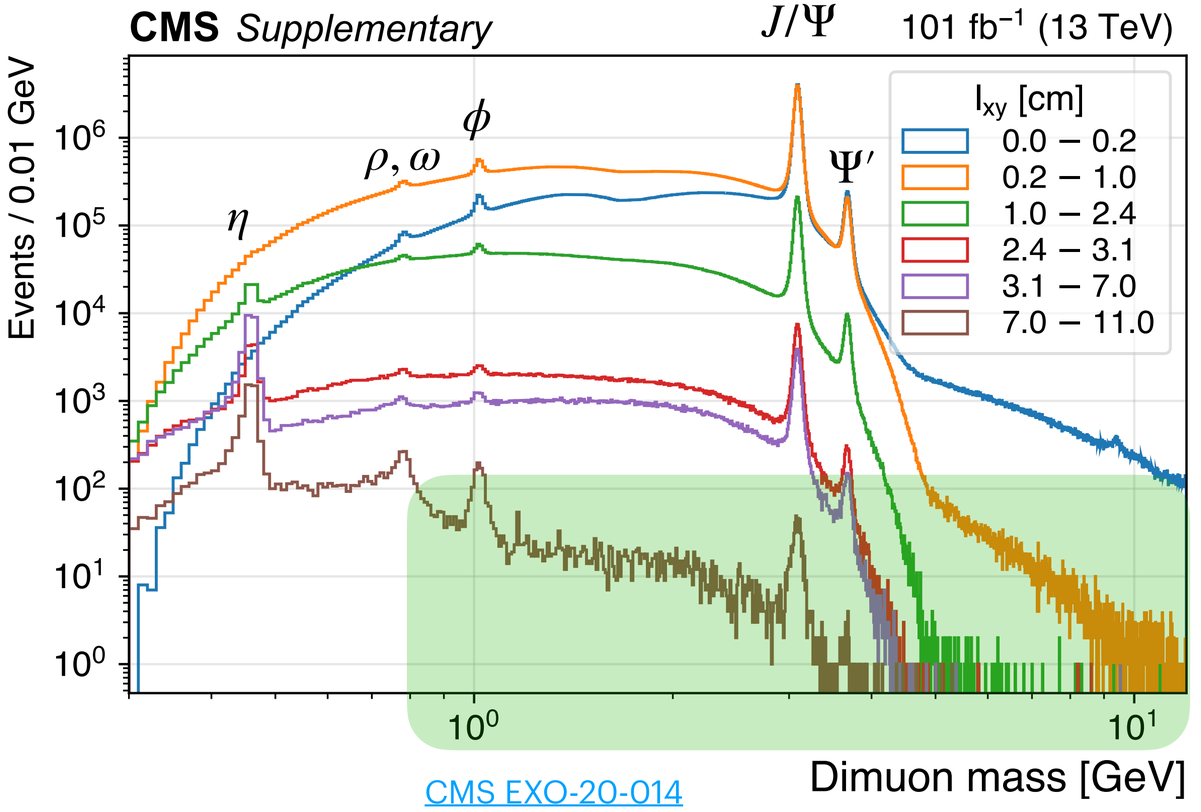
# Projected Sensitivity

- **Proton brem:** sensitivity with required number of $\mu^+\mu^-$ events, $p_T^\mu > 10$ GeV
- **Associated Production:**
  - sensitivity with required number of $e^+e^-$ events with $p_T^j > 25, p_T^e > 4$ GeV
  - sensitivity with $p_T^j > 25, p_T^e > 25$ GeV



# Preliminary background estimates

- SM sources of dimuons
  - Reduction of background events when requiring displaced vertex $\sim 0.1$ m
  - For $1 \lesssim m_{\mu\mu}/\mathrm{GeV} \lesssim 10$,
    $\sim 10$ events per bin for $\mathscr{L} \sim 100$ fb$^{-1}$
    - Projections for $\mathscr{L} = 3$ ab$^{-1}$:
      $\sim 300$ background events
    - need $\sim 20 - 100$ signal events for sensitivity
- Ongoing: exploring displaced dielectron background

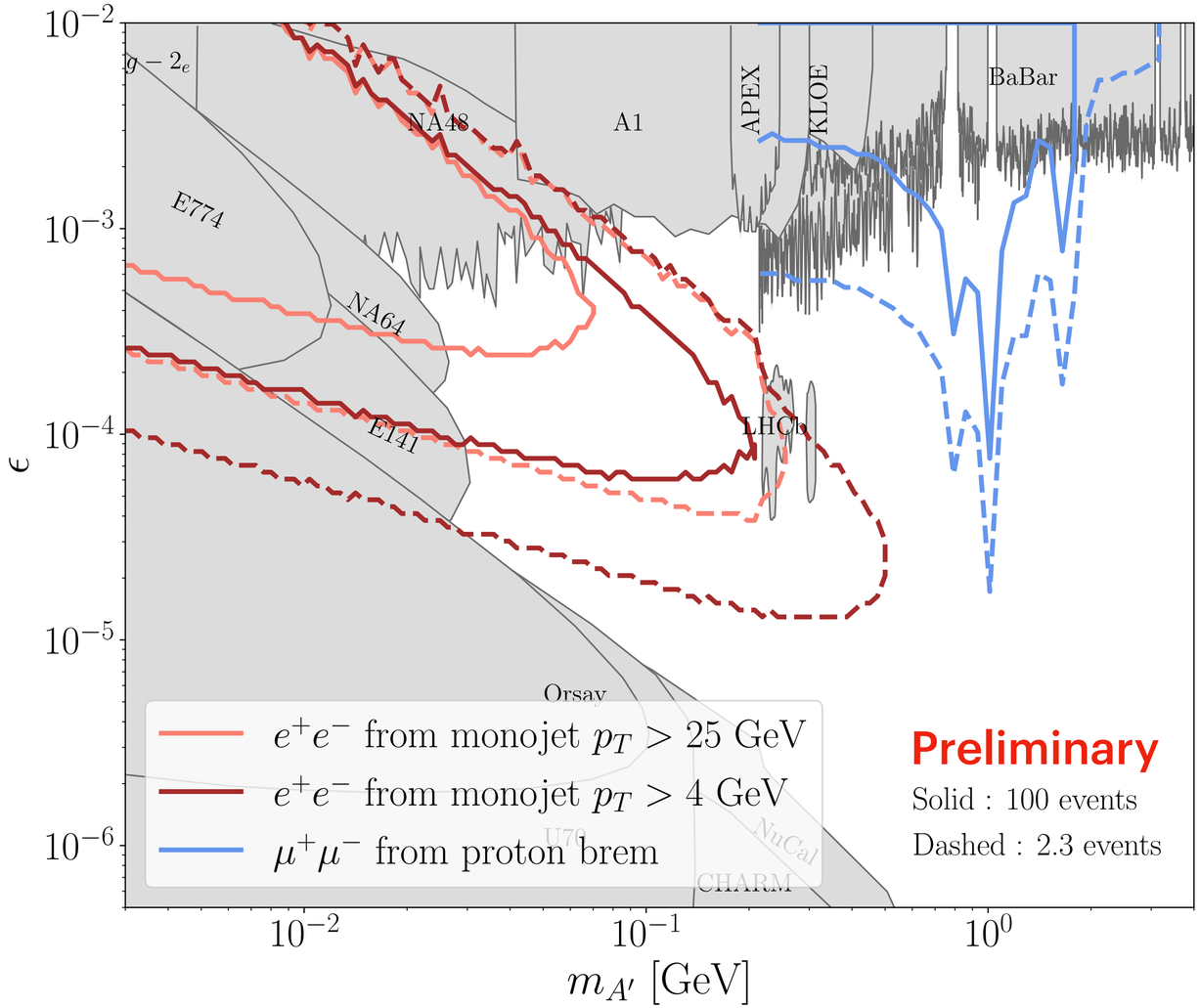



CMS EXO-20-014

# Can the LHC be sensitive to the Light Dark World?

- Short answer: We think so!
  - Requires thorough experimental analysis
- A novel method to probe yet unexplored parameter space for dark photons
- LHC can produce lots of light dark mediators like a beam dump experiment
  - Proton bremsstrahlung
  - Associated production
- Visible decays of light dark mediators can be observed in CMS detectors
  - backgrounds controlled by requiring displaced vertex, similar to LLPs
  - correlated signals depending on production mechanism

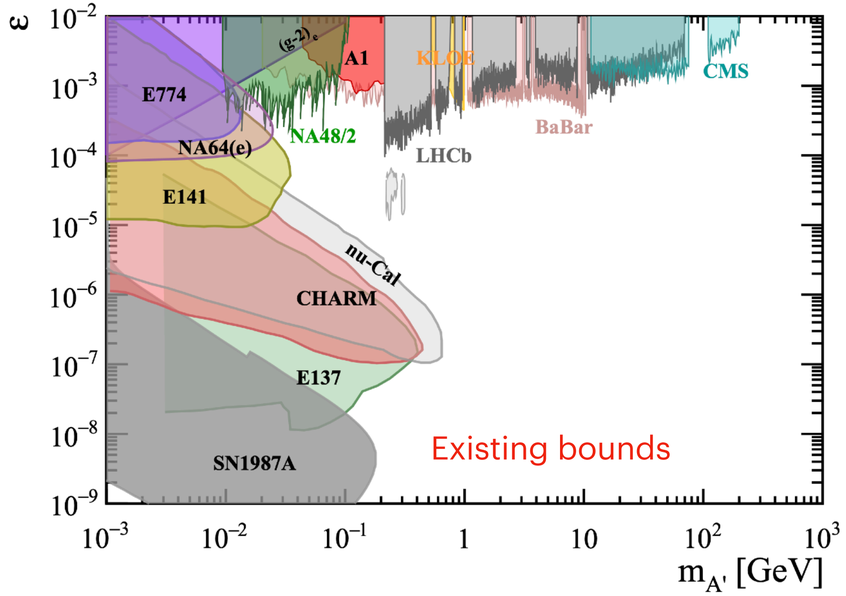
# Thank you!

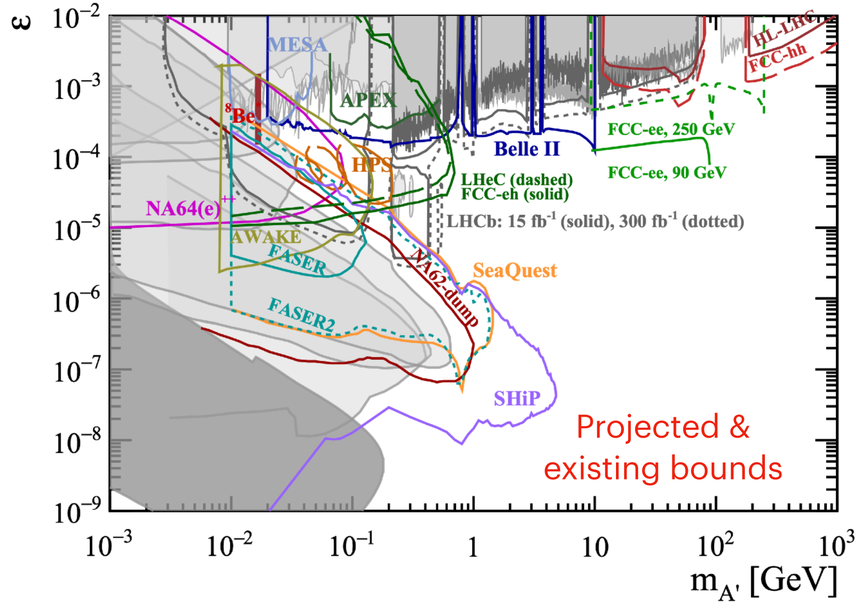

$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$\epsilon$
$g-2_e$
NA48
A1
APEX
KLOE
BaBar
E774
NA64
E141
LHCb
Orsay
U70
NuCal
CHARM
$e^+e^-$ from monojet $p_T > 25$ GeV
$e^+e^-$ from monojet $p_T > 4$ GeV
$\mu^+\mu^-$ from proton brem
Preliminary
Solid : 100 events
Dashed : 2.3 events
$10^{-2}$
$10^{-1}$
$10^{0}$
$m_{A'}$ [GeV]

# Dark Photon Model

- For a nice review, see [arXiv:2005.01515] Fabbrichesi, Gabrielli, Lanfranchi
  - Chapter 3 covers production and detection channels for massive dark photons

$$\mathcal{L}' = \left[\frac{e'}{\sqrt{1-\varepsilon^2}} J'_\mu - \frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu\right] A'^\mu + eJ_\mu A^\mu \,.$$



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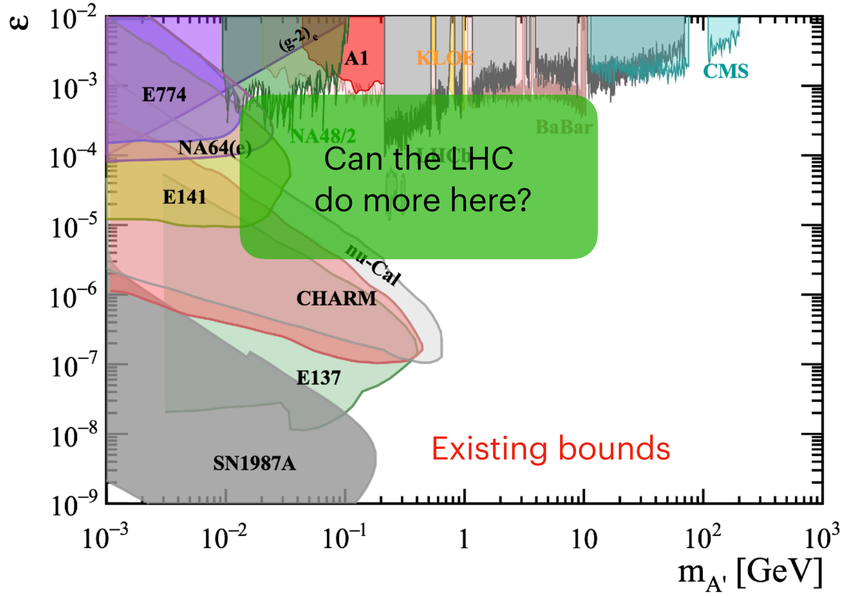
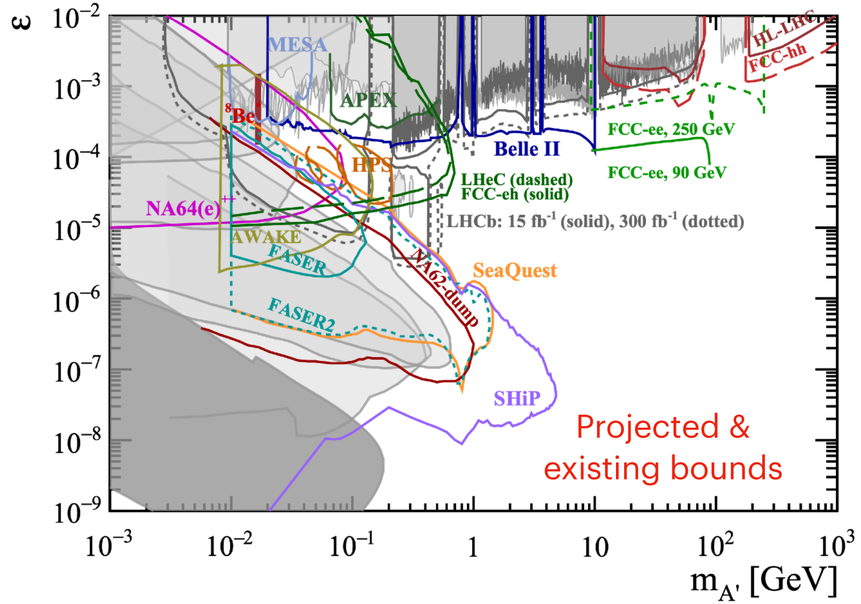
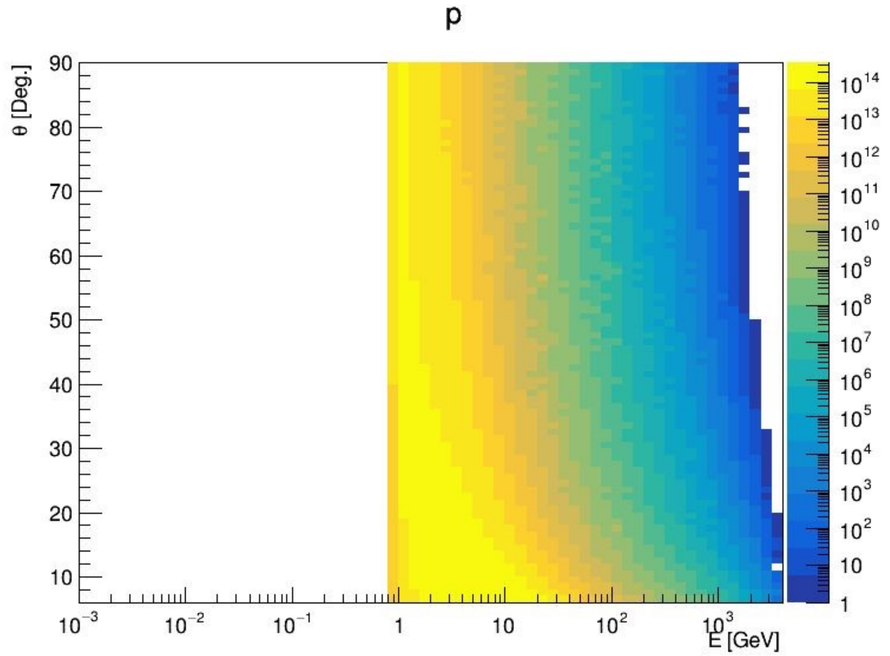
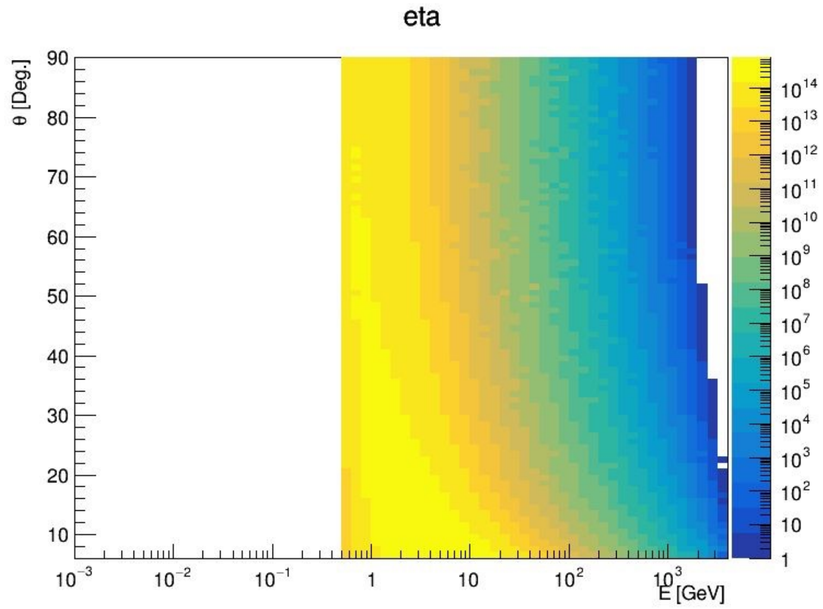


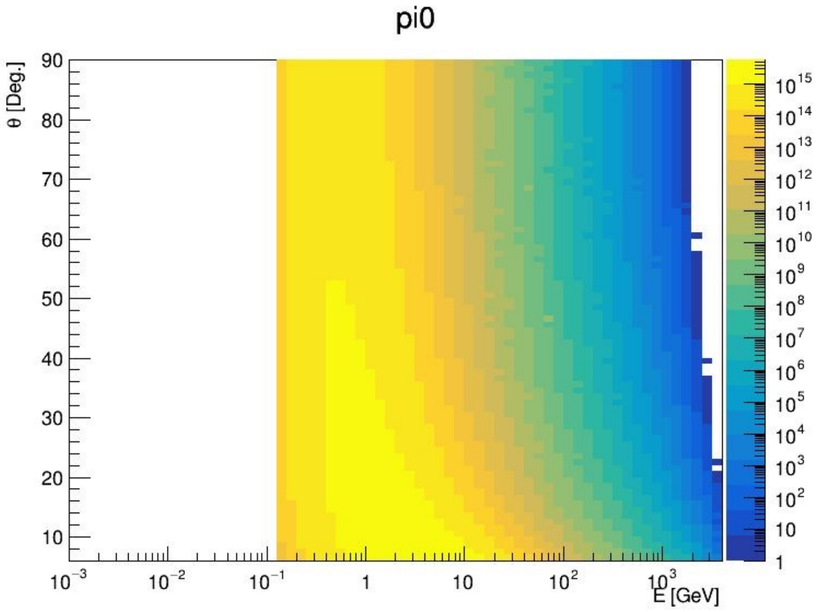



# Energy distributions

- proton & neutral meson fluxes from Pythia, with low energy parts cross-checked with EPOS LHC
- 2D histograms of $\theta$ and $E$ for $1\ \mathrm{ab}^{-1}$

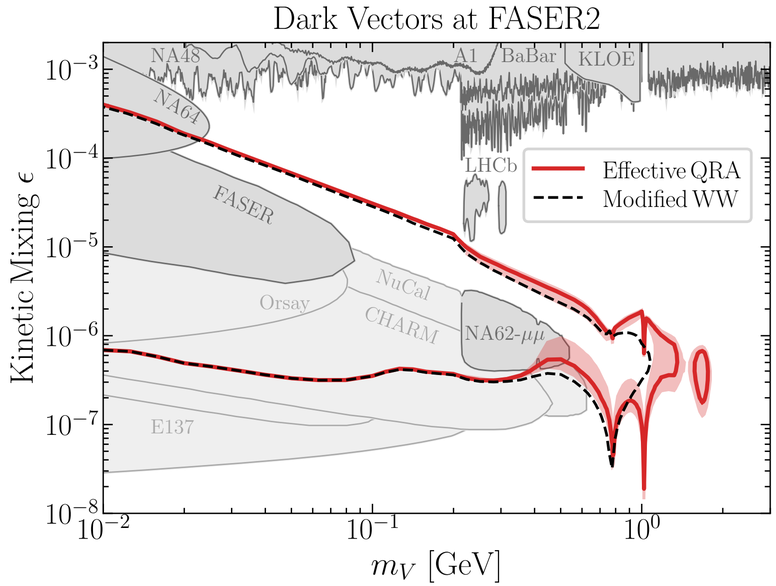


# Comparison to FASER(2), SHiP

- FASER similar to DUNE ND, long survival distance $\sim 480$ m needed
- Updated FASER results from 2026 shown in latest sensitivity plot
- SHiP has shorter survival length $< 100$ m




[2409.09123] Foroughi-Abari, Reimitz, Ritz