Long-lived particles at Belle II.

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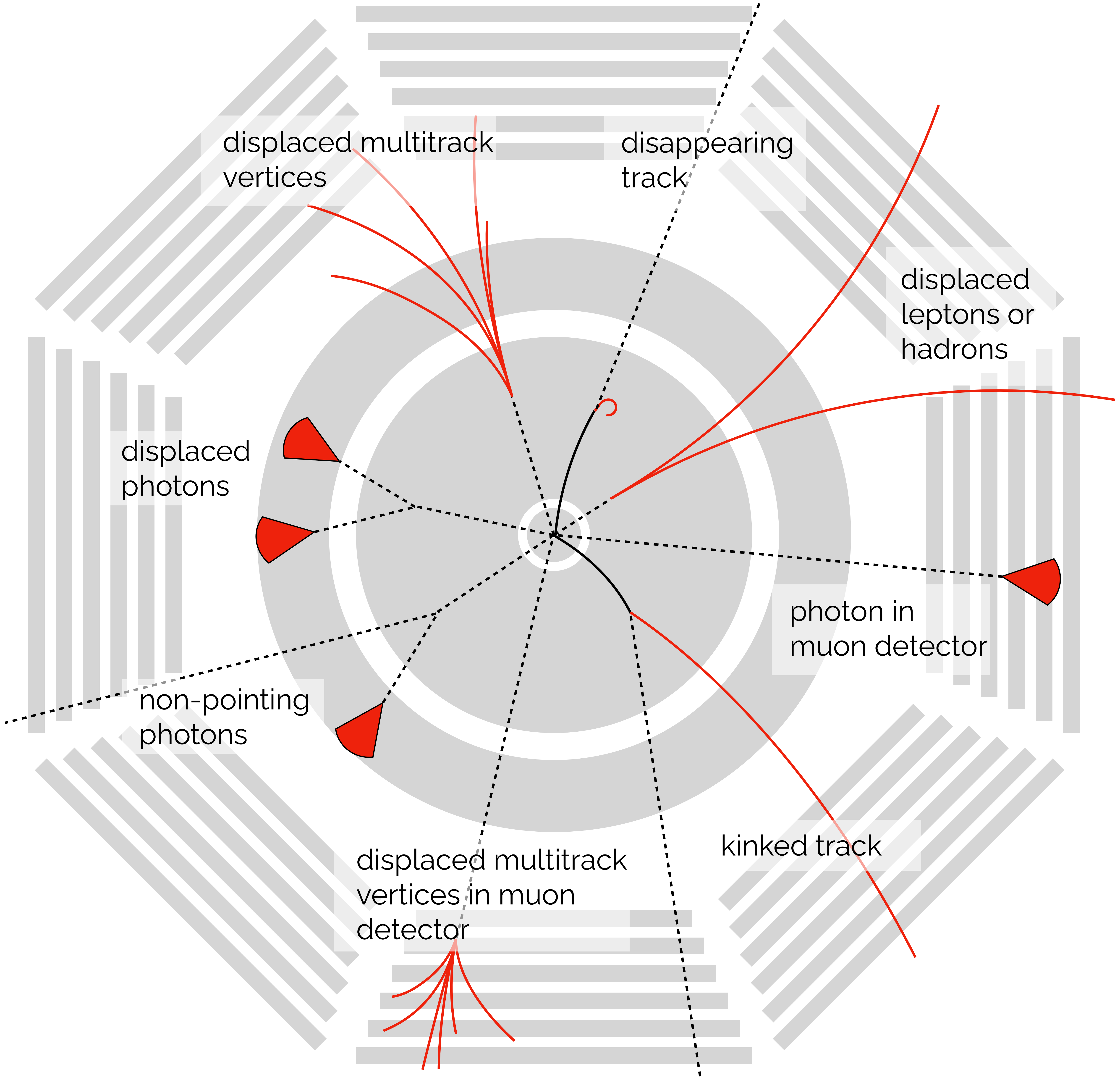
Belle II Germany Meeting, 14.09.2020

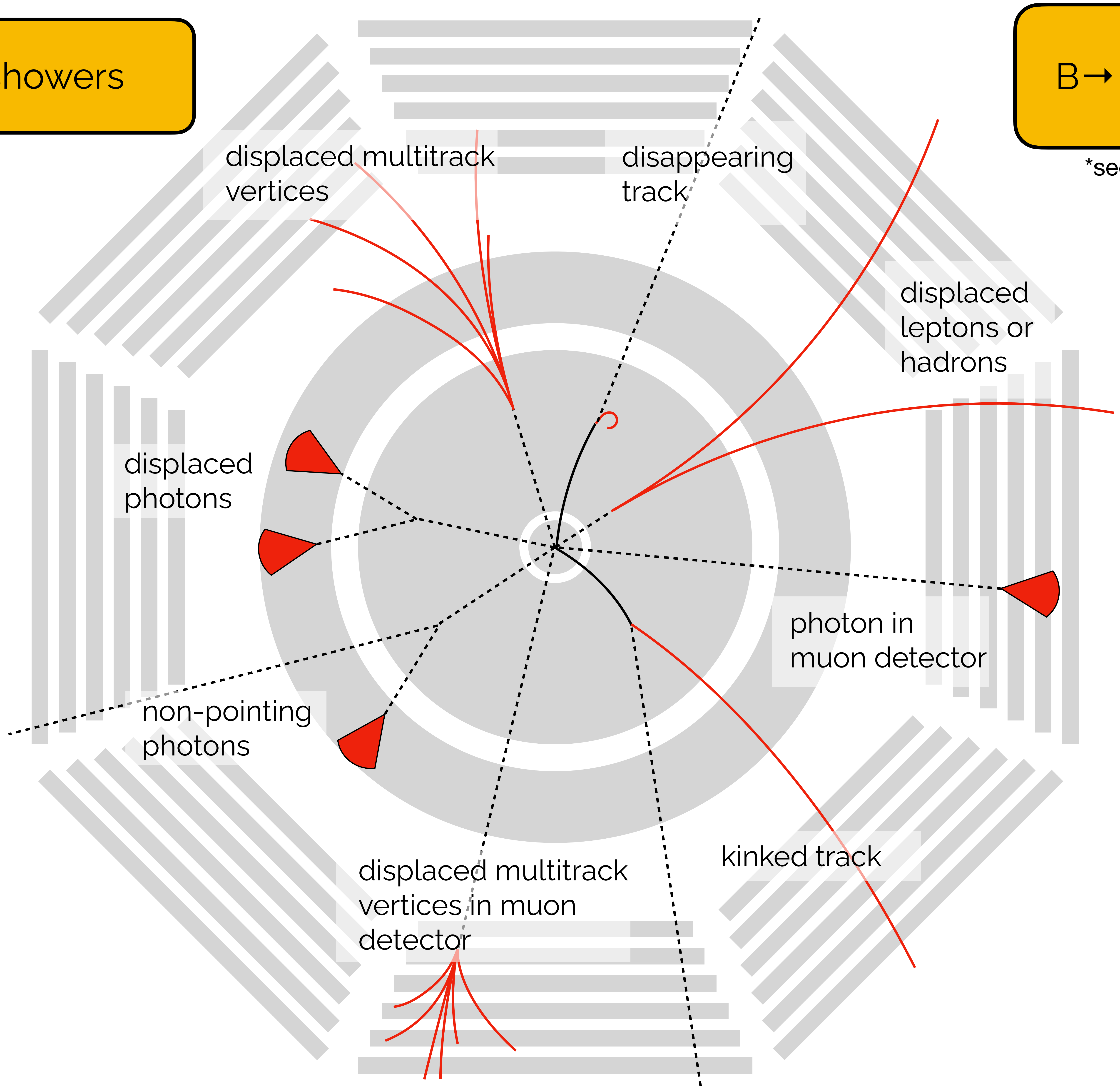
with contributions from:
M. Dolan, M. Duerr, A. Filimonova, C. Garcia-Cely, C. Hearty, F. Kahlhoefer,
K. Schmidt-Hoberg, R. Schäfer, M. Tammaro, K. Trabelsi, S. Westhoff, J. Zupan

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
DESY.


displaced multitrack vertices
disappearing track
displaced leptons or hadrons
displaced photons
photon in muon detector
non-pointing photons
kinked track
displaced multitrack vertices in muon detector

dark showers

light ALPs
multi ALP models
B→Ka

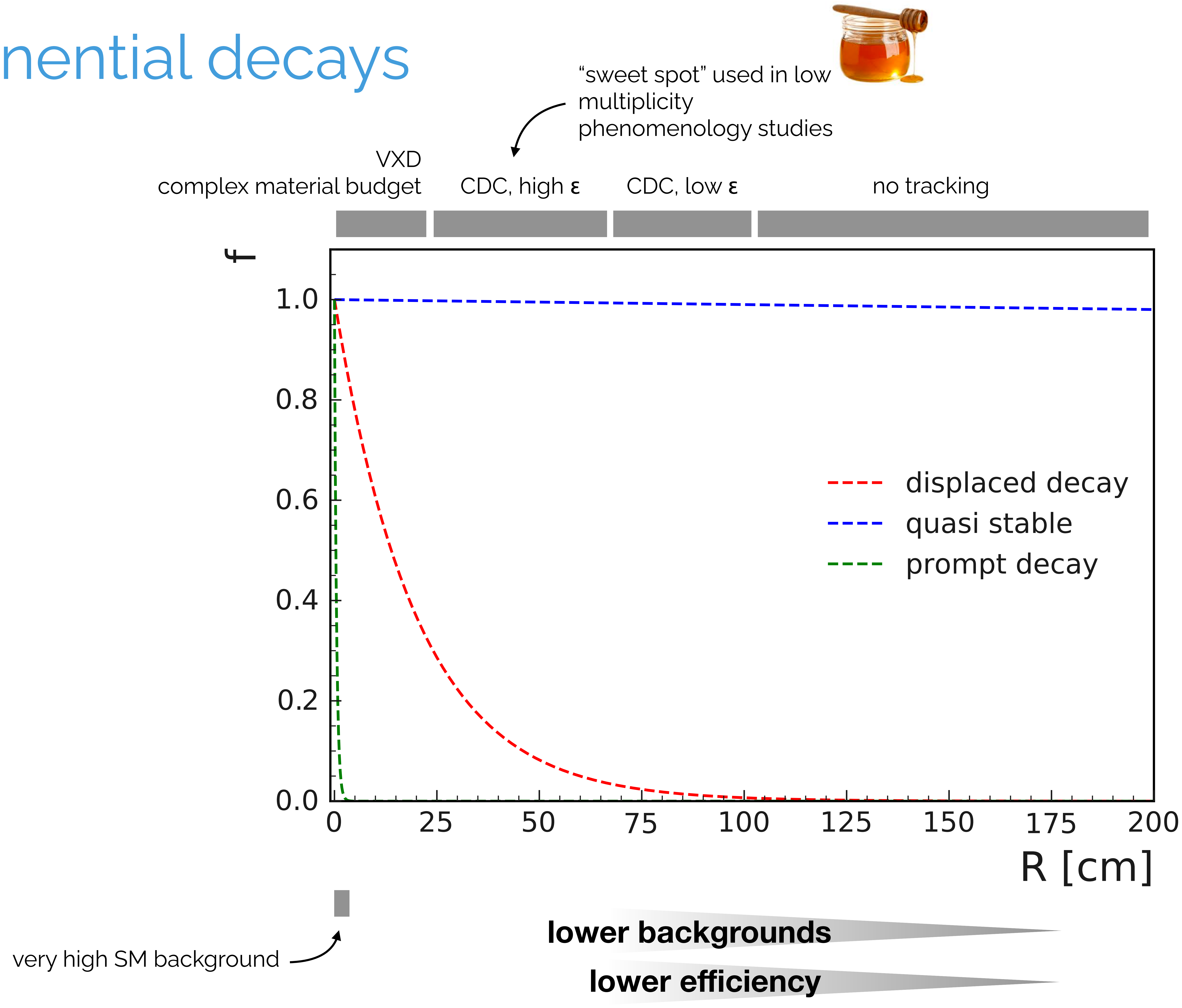


B→ KS (*), iDM, iDM+DH

*see talk by Sam Cunliffe

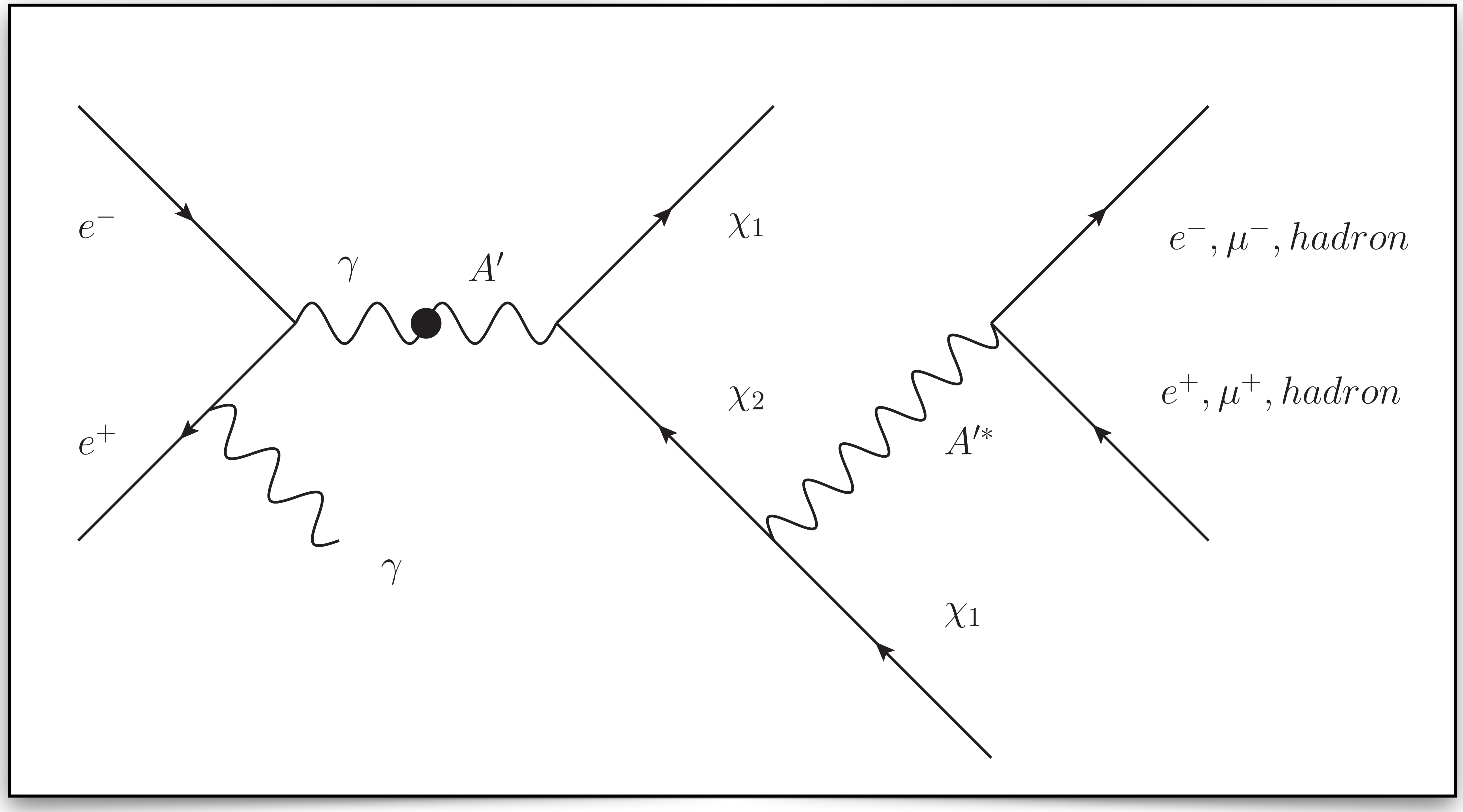
GAZELLE

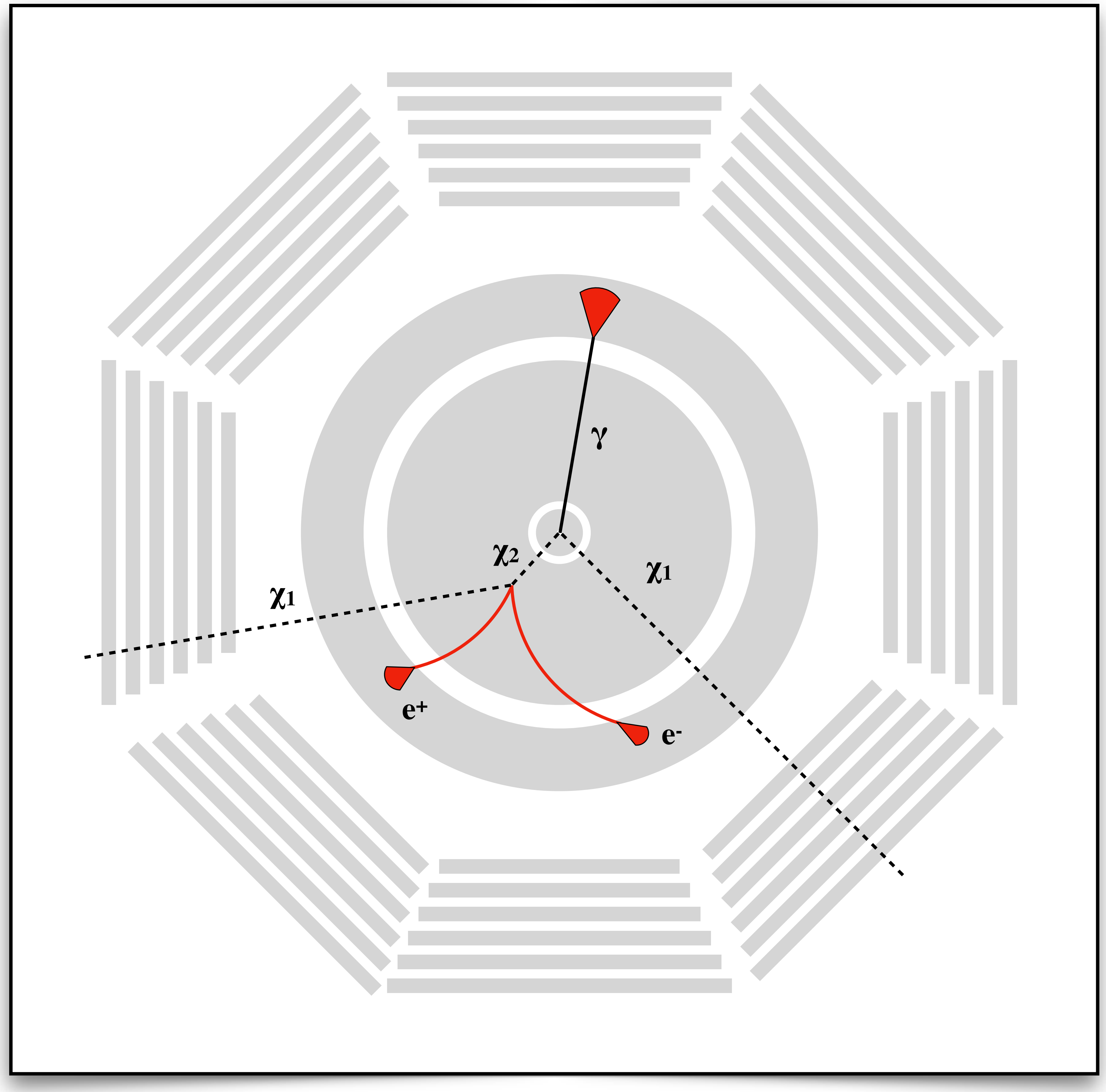
Exponential decays



Inelastic Dark Matter

analysis has started





M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, JHEP 02 (2020) 039

Inelastic Dark Matter

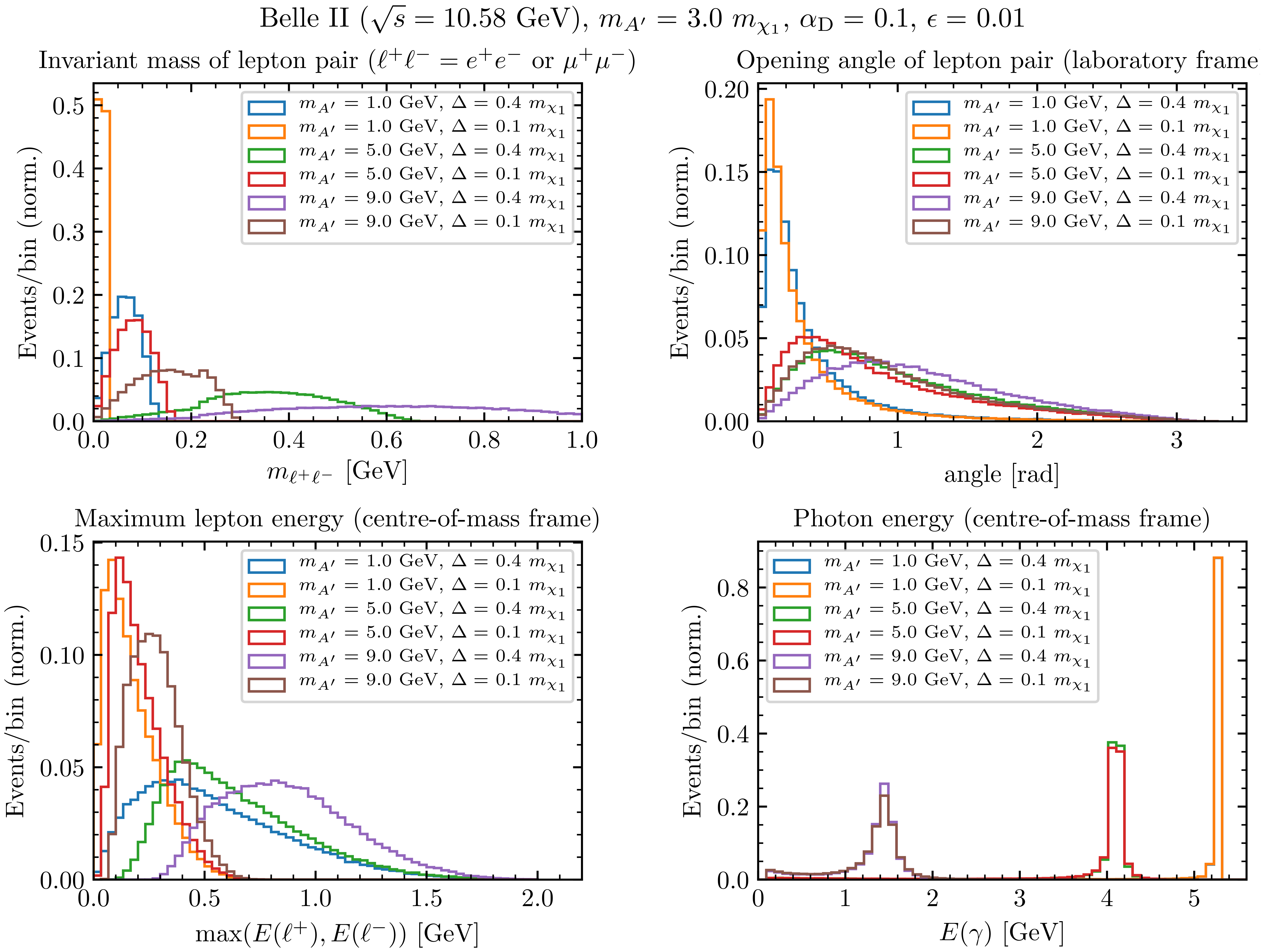
M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, JHEP 02 (2020) 039

Δ large, A' heavy → $m_{\ell\ell}$ large

A' heavy → large opening angle

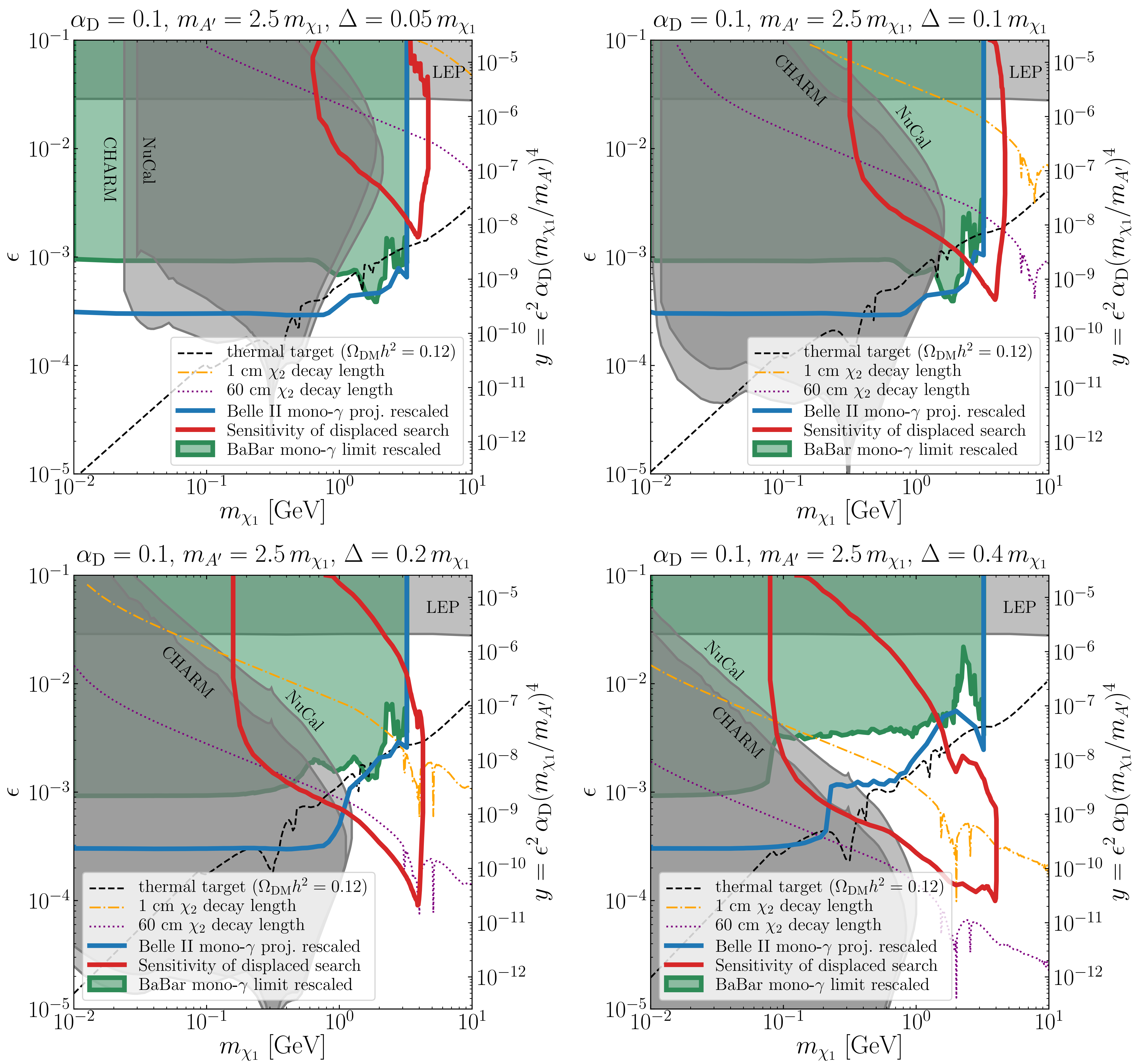
Δ large → high momentum

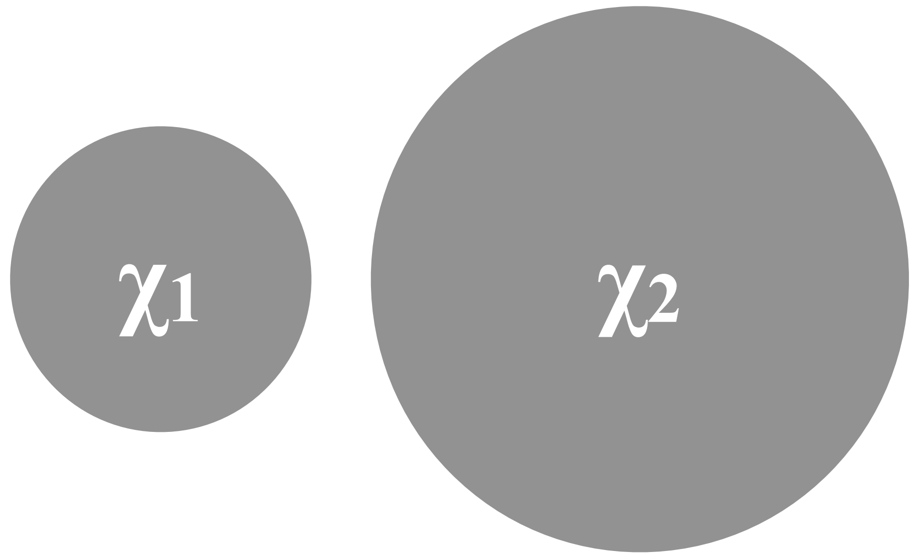
photon energy ↔ A' mass

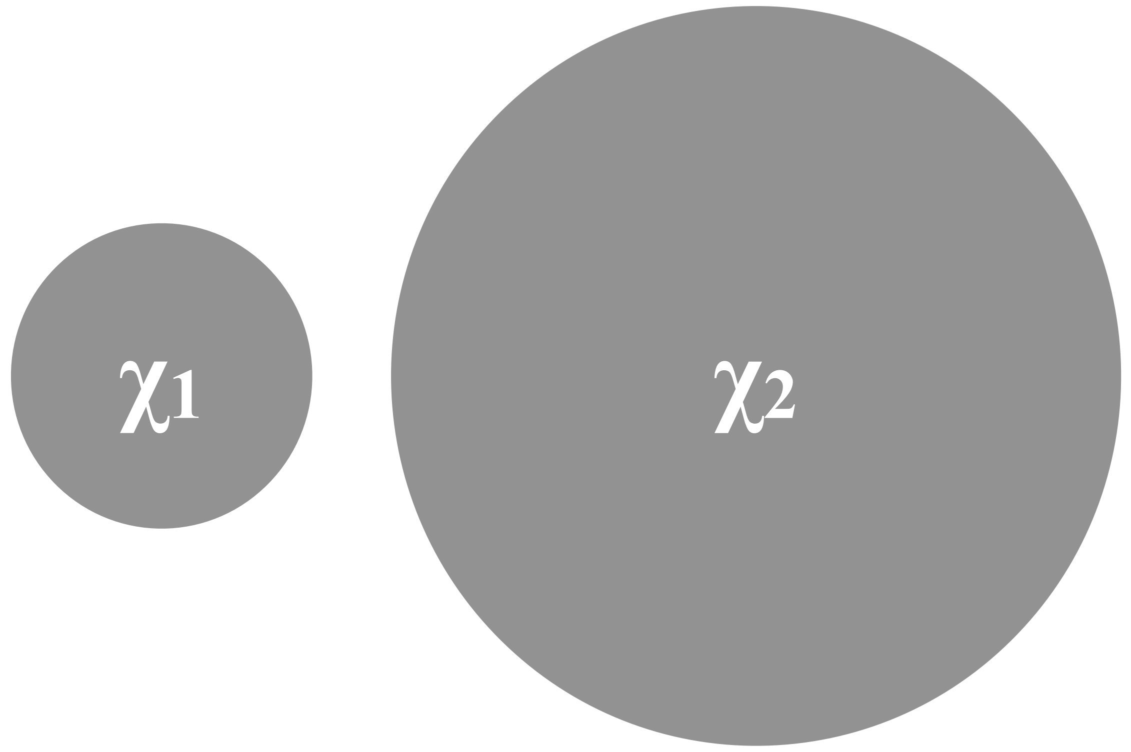


Inelastic Dark Matter

M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, JHEP 02 (2020) 039



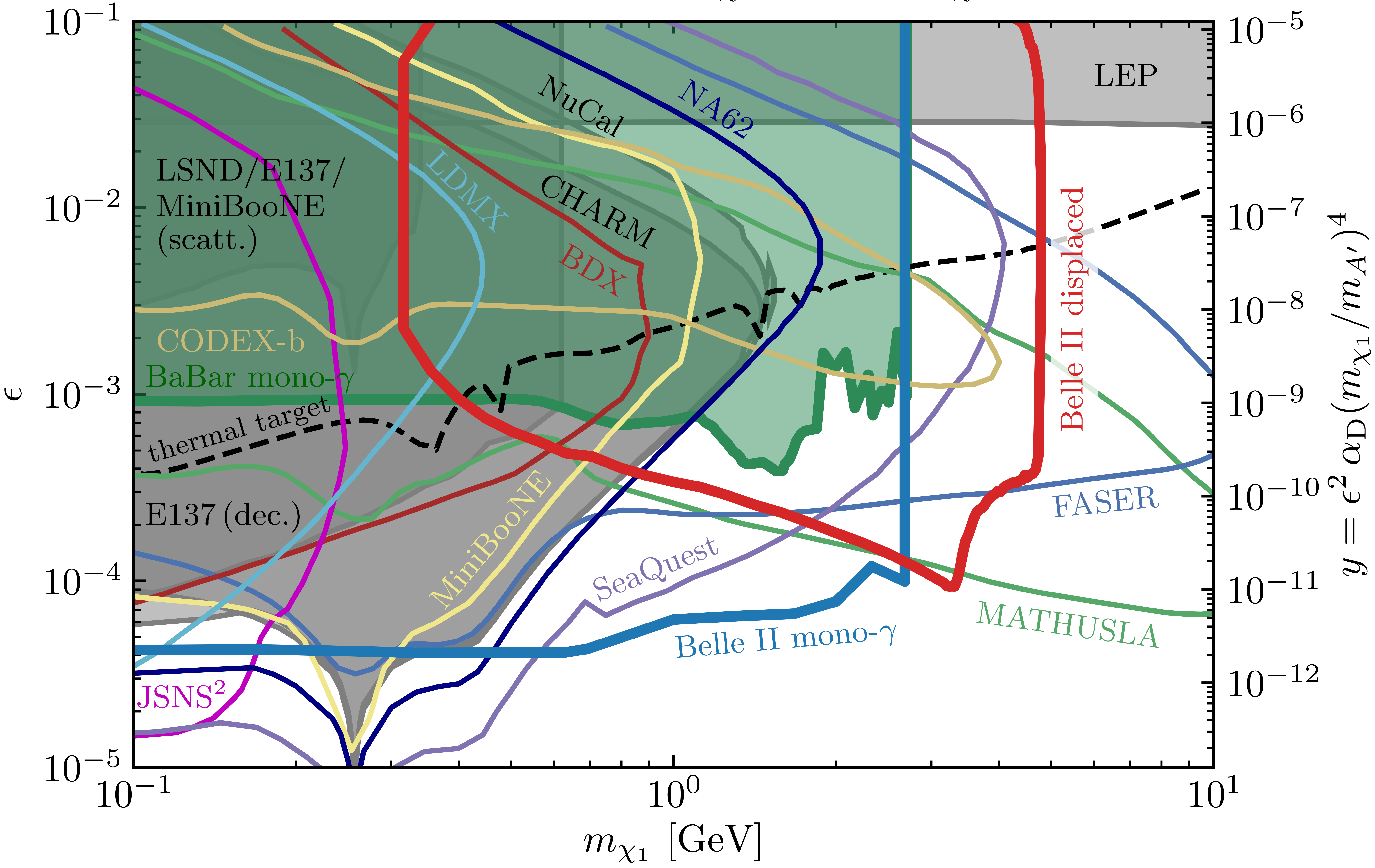




Inelastic Dark Matter

M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, JHEP 02 (2020) 039

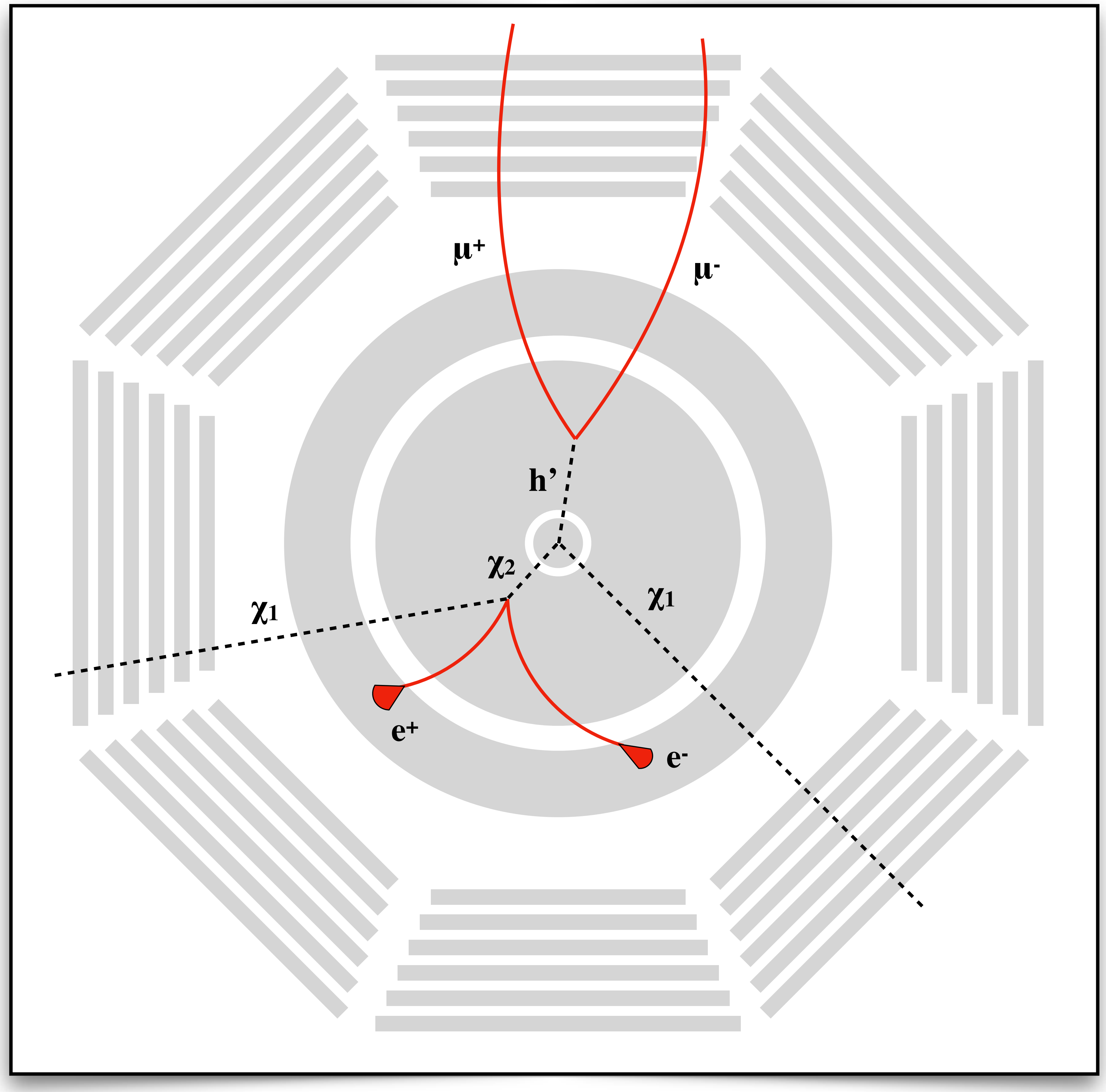
$\alpha_D = 0.1,\ m_{A'} = 3\,m_{\chi_1},\ \Delta = 0.1\,m_{\chi_1}$

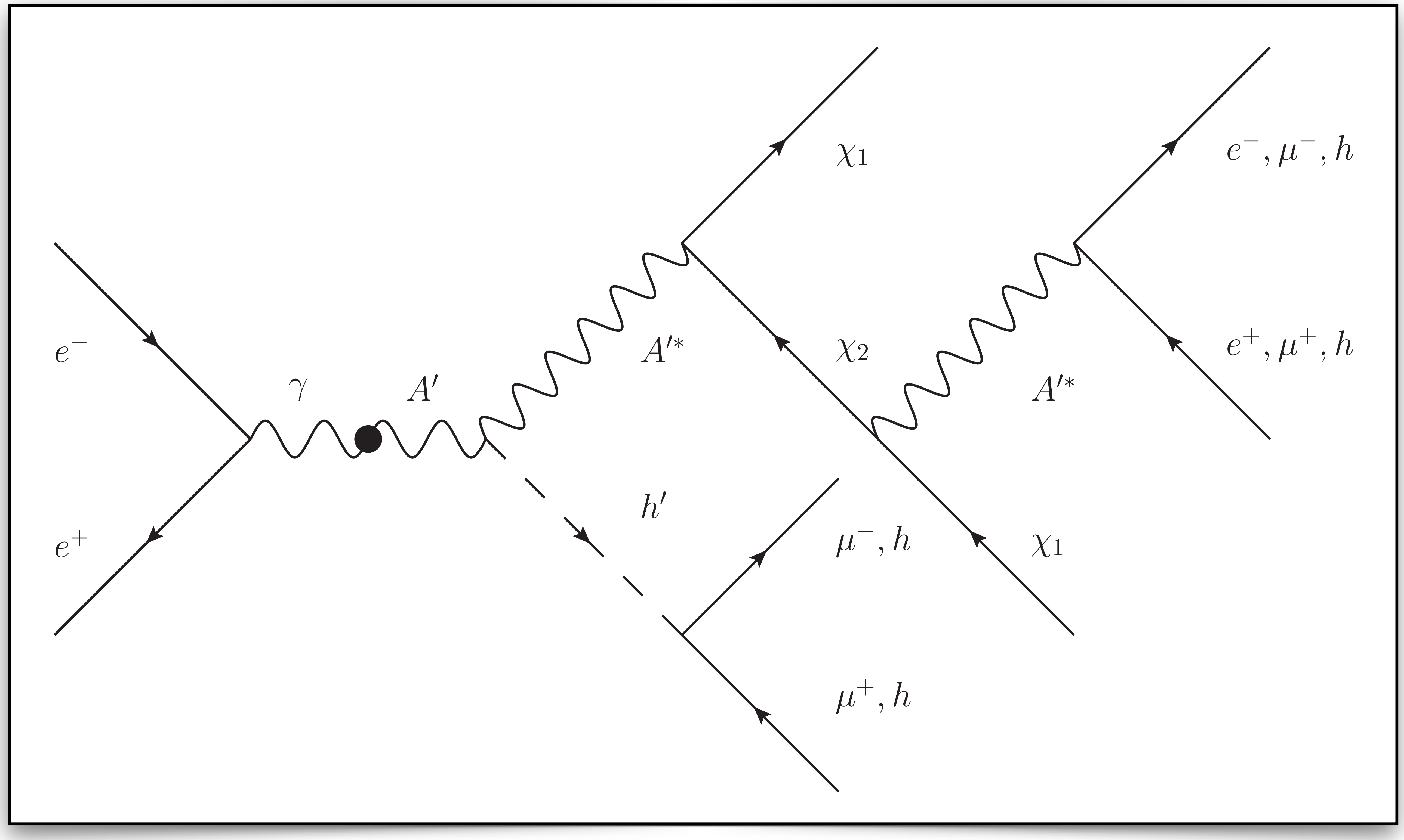


Inelastic Dark Matter with Dark Higgs

theory paper in preparation

M. Duerr, **TF**, C. Hearty, C. Garcia-Cely, K. Schmidt-Hoberg (in preparation)





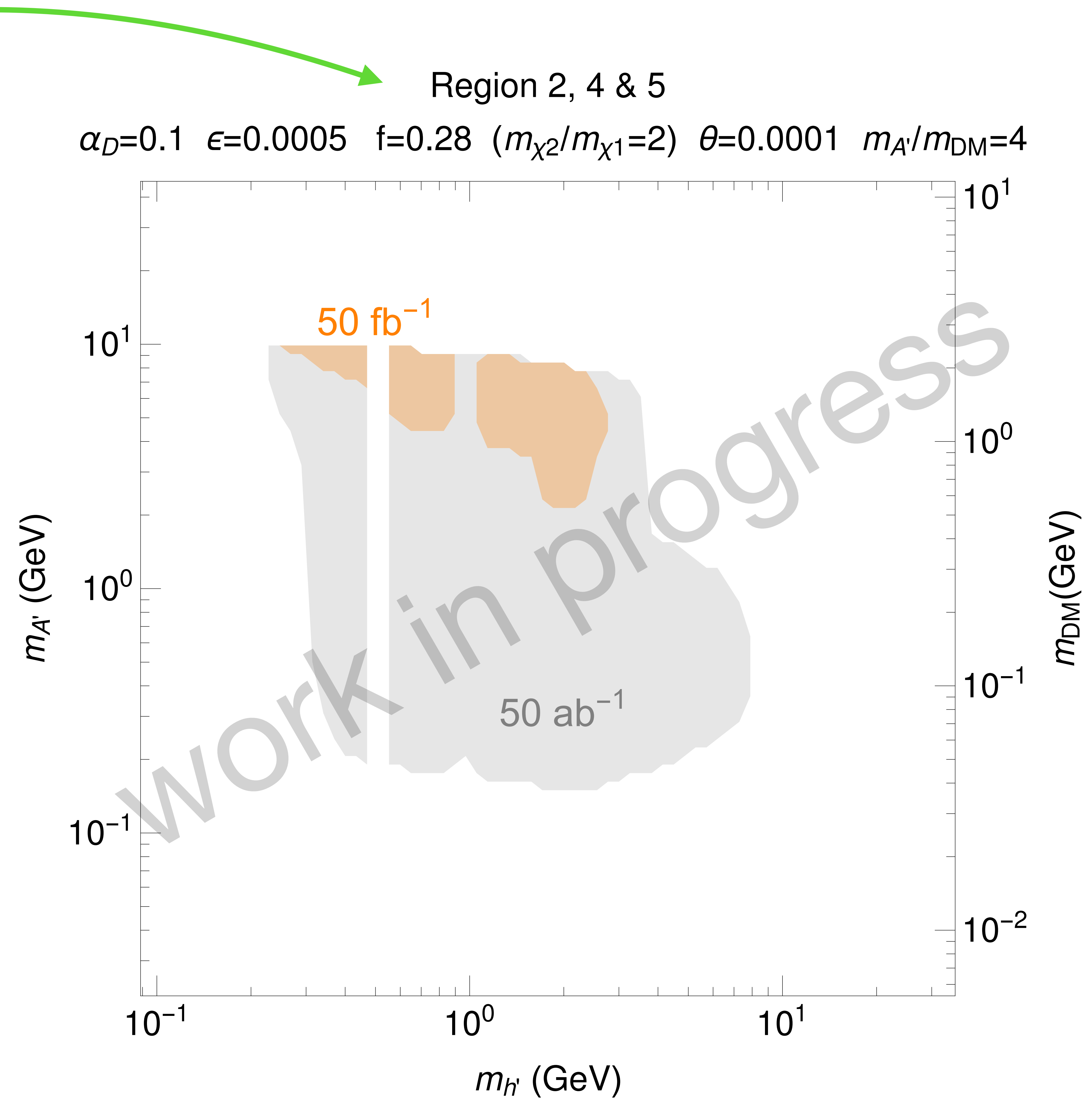
Inelastic Dark Matter with a Dark Higgs

prompt displaced

	$R_\phi < 1\,\mathrm{cm}$	$20 < R_\phi < 60\,\mathrm{cm}$	$R_\phi > 150\,\mathrm{cm}$
$R_{\chi_2} < 1\,\mathrm{cm}$	1	2	3
$20 < R_{\chi_2} < 60\,\mathrm{cm}$	4	5	6
$R_{\chi_2} > 150\,\mathrm{cm}$	7	8	9

invisible

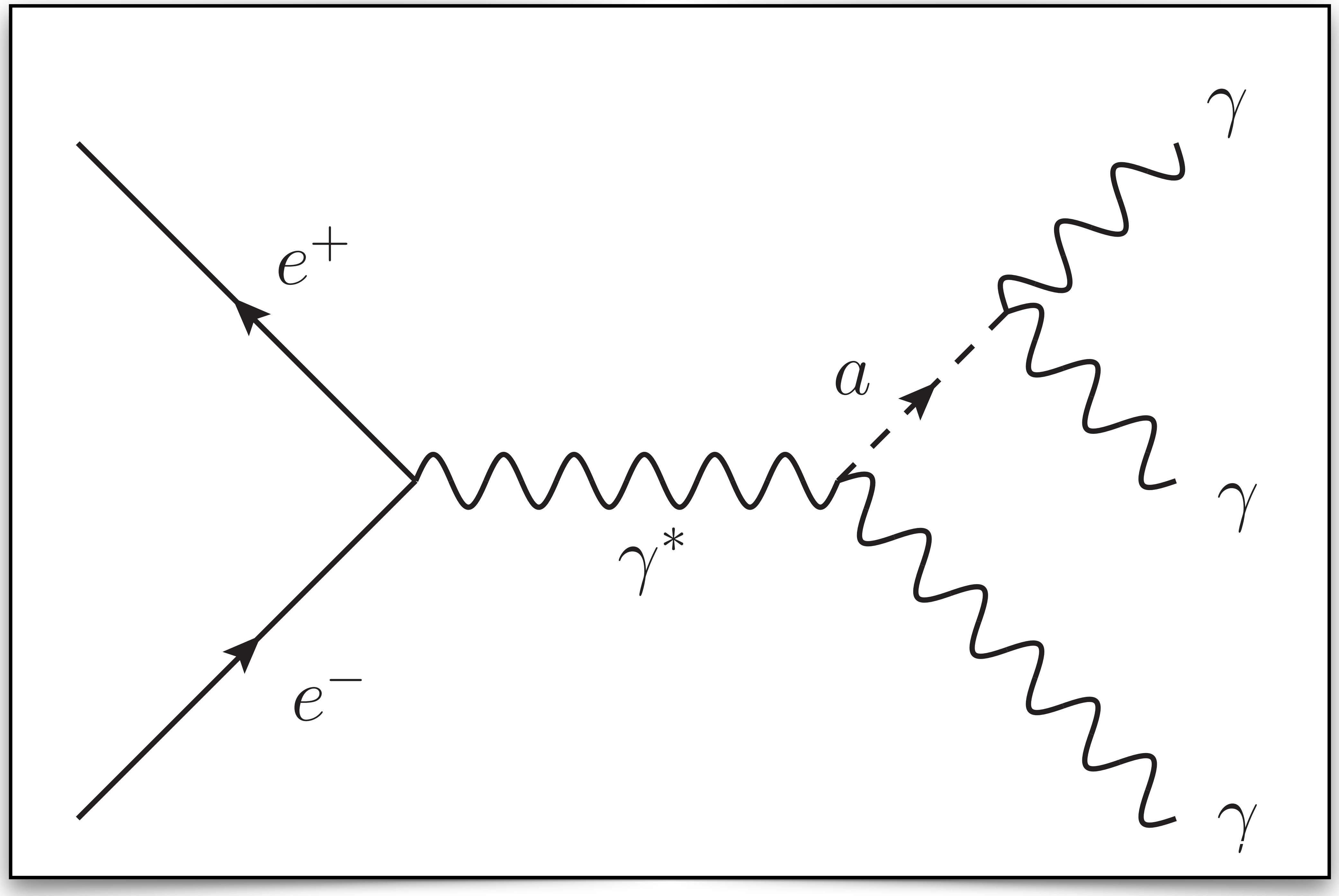
- Trigger is very challenging and efficiency varies over the parameter space:
  - three isolated clusters (one > 500 MeV)
  - four isolated clusters (> 180 MeV)
  - two tracks with large opening angle (prompt only)
  - three tracks (prompt only)
  - proposed: displaced vertex trigger (20<R<60cm, pt > 100 MeV)

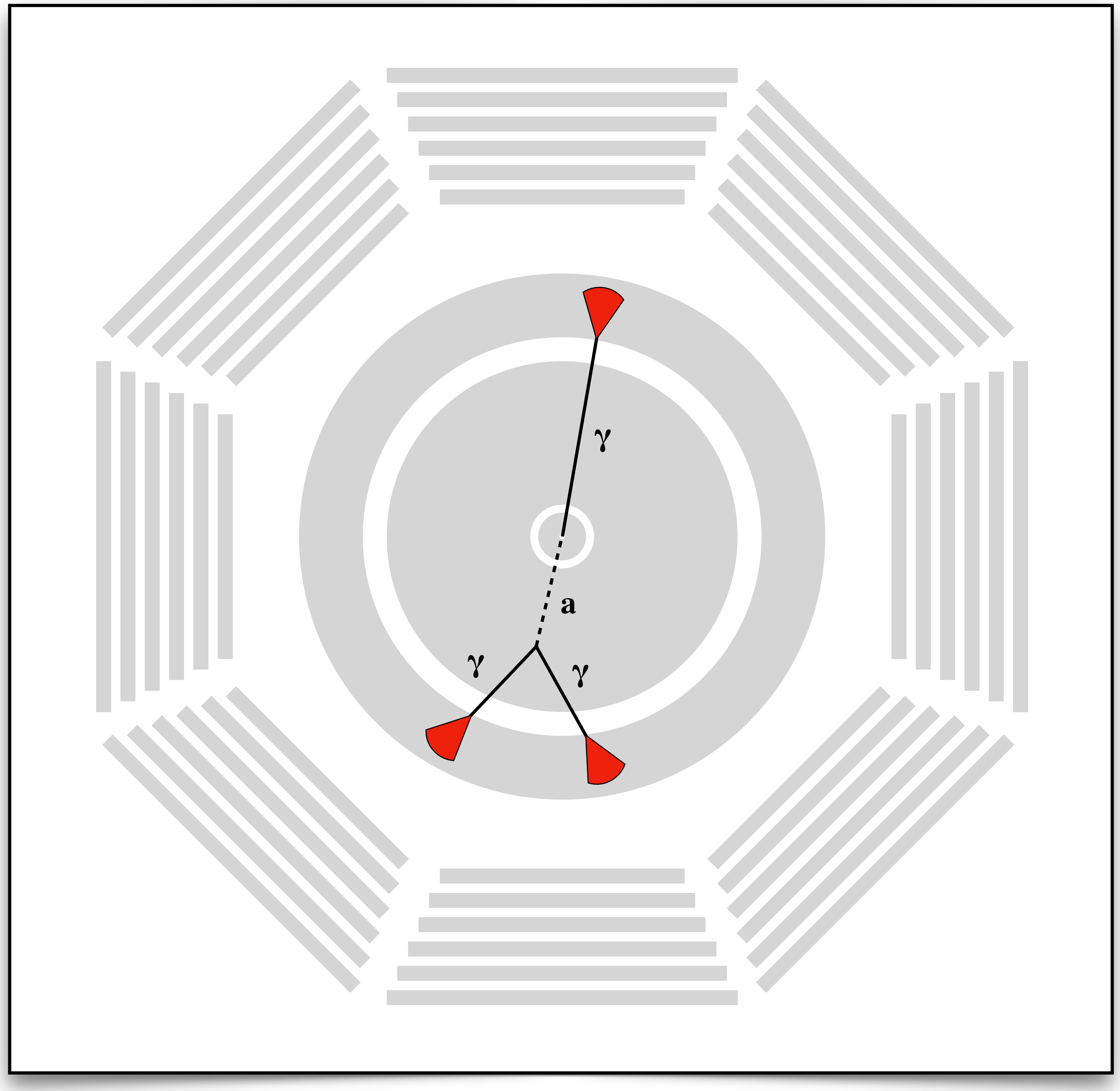


M. Duerr, **TF**, C. Hearty, C. Garcia-Cely, K. Schmidt-Hoberg (in preparation)

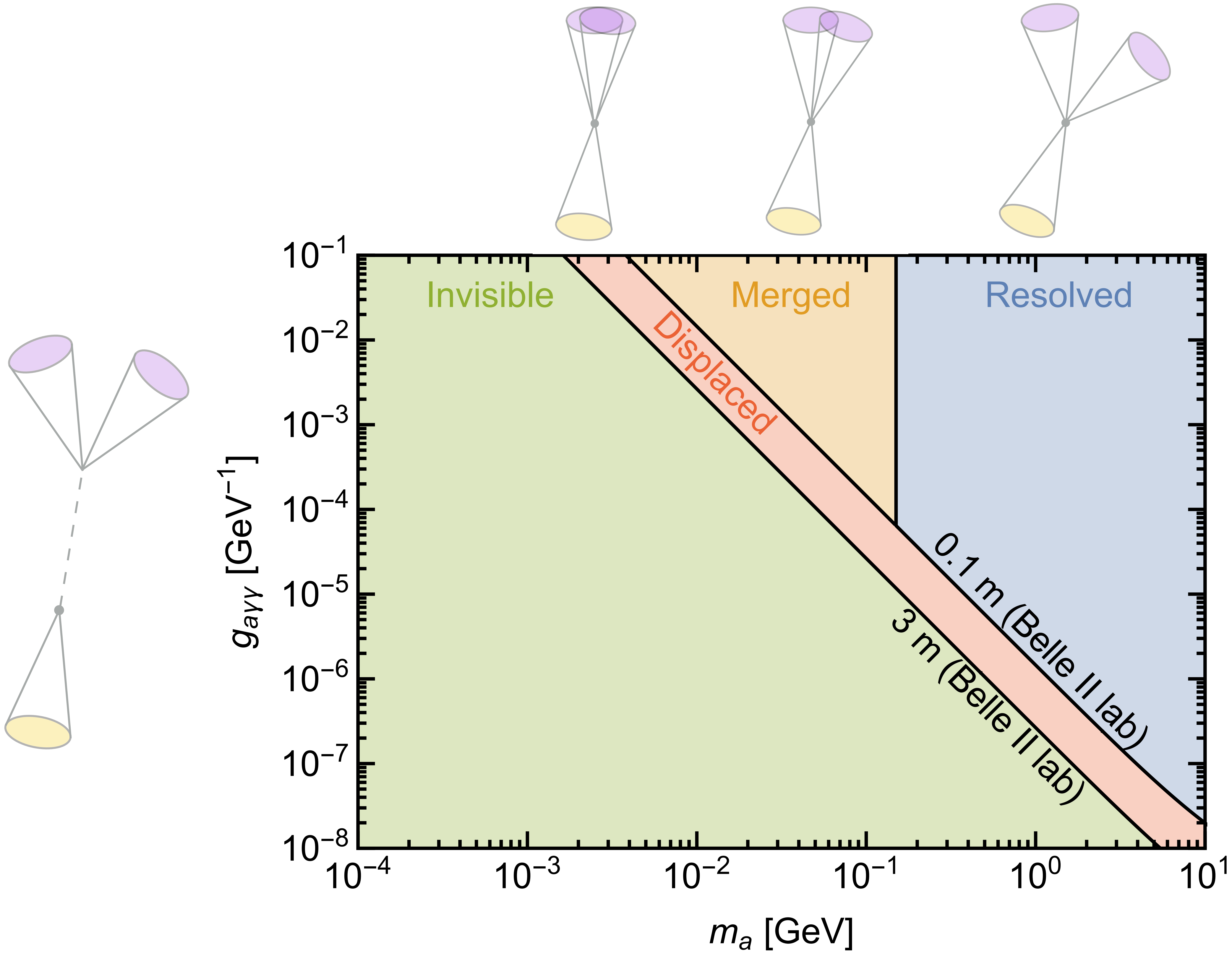
Long-lived ALPs

analysis in preparation (new PhD starting soon)





Long-lived ALPs

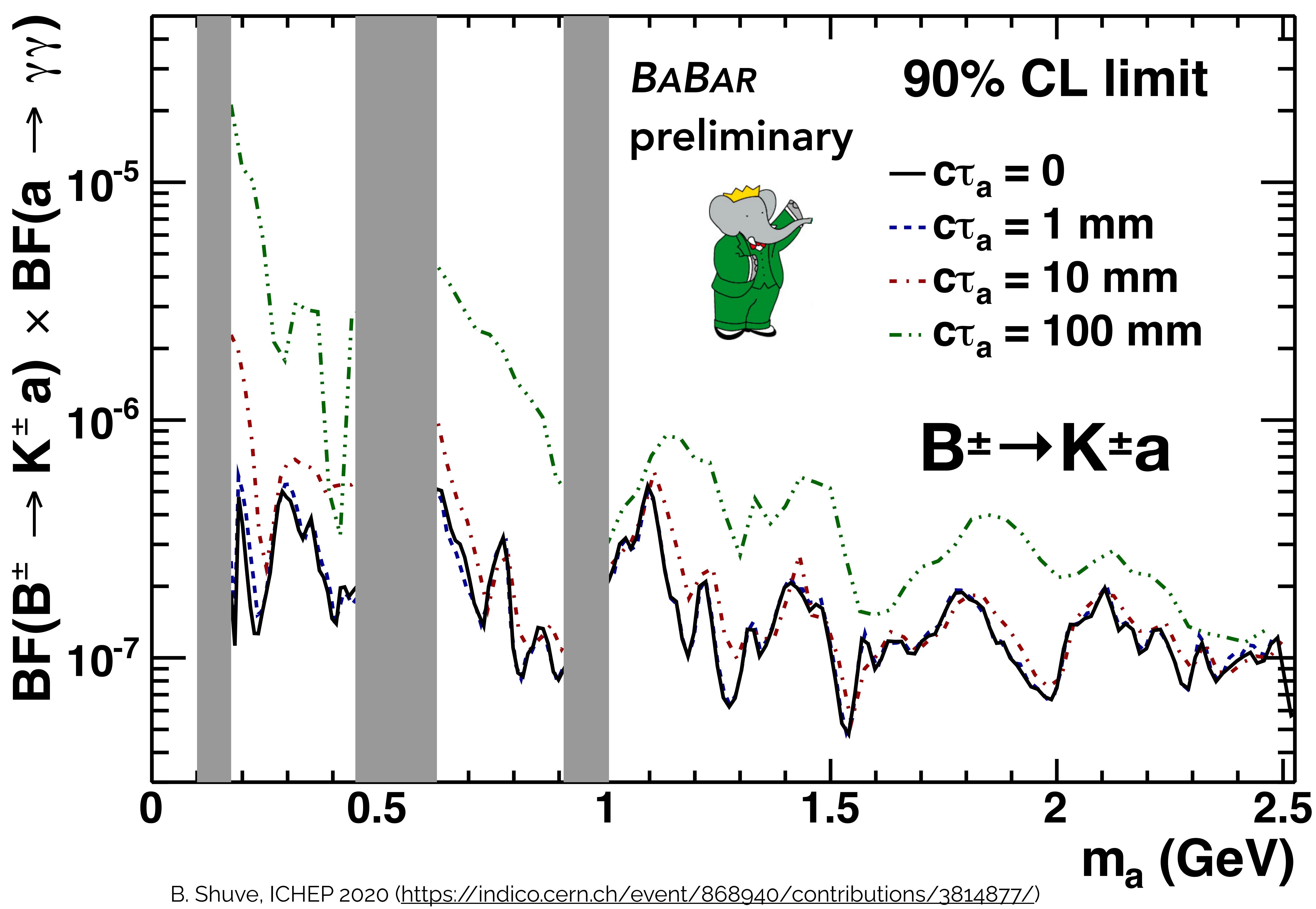


for couplings $g_{a\gamma\gamma} < 10^{-4}$ a sizeable fraction of ALP decays is long-lived

M. Dolan,. **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, JHEP 1712 (2017) 094

Long-lived ALPs

if production and decay have different mechanisms, LLPs do not necessarily come with tiny couplings



B. Shuve, ICHEP 2020 (https://indico.cern.ch/event/868940/contributions/3814877/)

- no dedicated optimization in BaBar analysis:
  - efficiency loss from photon shower shape distortion
  - energy bias for LLP ALPs

GAZELLE: A dedicated LLP detector for Belle II

GAZELLE: "GAZELLE is the Approximately Zero-background Experiment for Long-Lived Exotics"

- This is not yet an proposal or a TDR - we are currently investigating the physics reach and backgrounds, and are preparing a white paper in the context of the US snowmass process
- Basic design (not studied in detail yet):
  - "Cheap" O(5×5×5)m^3 detector with O(10cm) tracking and O(100 ps) timing resolutions, O(1m) concrete shielding, O(20m) away from Belle II IP
    - Add on option 1: high granularity calorimeter for decays into neutrals
    - Add on option 2: lead/emulsion targets (like OPERA) e.g. X Chen, Z. Hou, Y Wu (arXiv:2001.0438)
  - Synchronized readout with Belle II to exploit e^+e^- kinematics
  - Belle II triggers GAZELLE and vice versa (maximum distance limited by L1 latency)

GAZELLE: Physics and backgrounds

easy

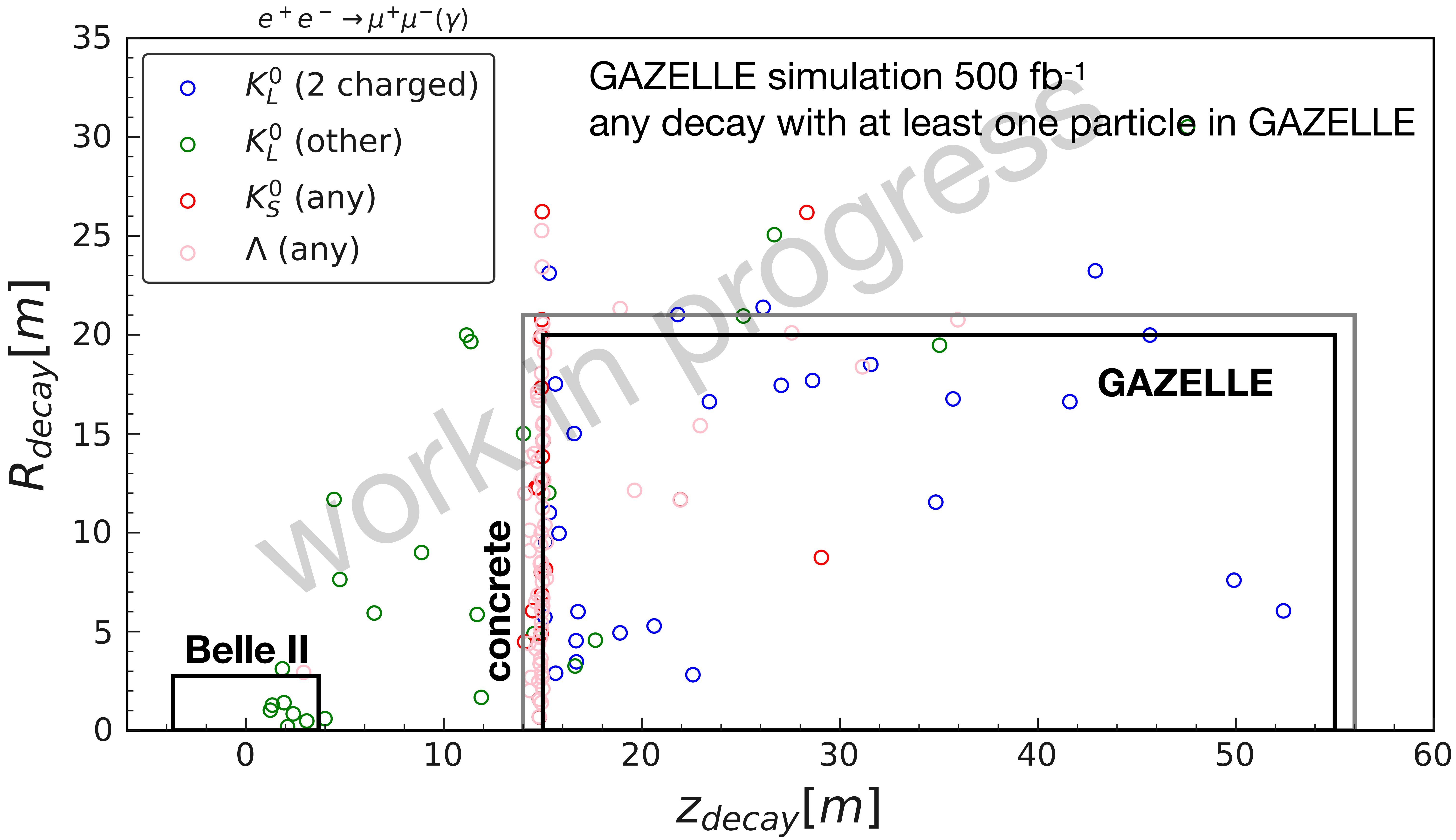
- Benchmark models under investigation:
  - B→KS (light scalar mixing with Higgs)
  - B±→Nℓ±, B→ND±ℓ±, τ→Nπ± (heavy neutral leptons)
  - ALPs
  - Light Dark Photons A'
  - inelastic DM

hard

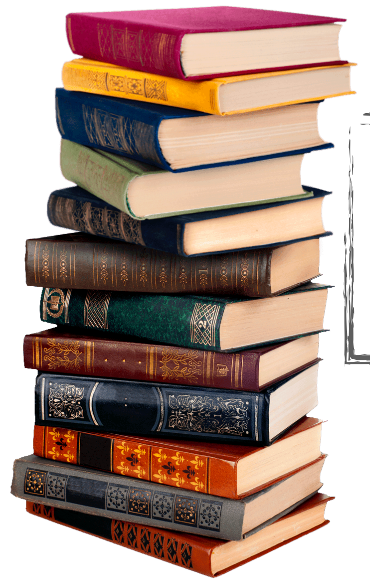
- Backgrounds under investigation:
  - $\mu + A \to K_L^0/K_S^0/\Lambda + X$, $K_L^0 \to \pi\pi\pi^0$ or $K_L^0 \to \pi\ell\nu$ from cosmics and ee→μμ(γ)
  - $\mu \to \pi\ell\nu$ (decays in flight) from cosmics and ee→μμ(γ)
  - K_L^0, K_S^0, Λ from continuum and B decays
  - neutrons

Backgrounds: $\mu + A \rightarrow K_L^0/K_S^0/\Lambda + X$

- Reduction possible:
  - For beam muons (see plot):
    - veto muons in Belle II (~99%)
    - use cuts on pointing angles to reduce 3-body decays
  - For cosmic muons:
    - correlate with Belle II trigger time
    - use pointing information from 3-body decays
    - need a muon veto on top?



Letter of interest for Snowmass 2021



For Snowmass Phase 1:
LOI (1,500 in total)

RF6-2 Letter of Interest (LOI) for Snowmass 2021: Long-lived particles at Belle II

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R. Schäfer,[5] M. Tammaro,[6,7] K. Trabelsi,[8] S. Westhoff,[5,*] and J. Zupan[6]

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We plan to explore the full potential of Belle II to search for GeV-scale hidden sectors with long-lived particles. This requires the development of new search strategies for charged and neutral final states, including new reconstruction algorithms and optimized triggers. Motivated by the particle dark matter hypothesis, we plan to define simple models as representatives of a mechanism that sets the relic abundance in the early universe, like co-scattering or freeze-in. Based on these models, we predict typical signatures with long-lived particles that guide the new searches at Belle II. In addition we plan to explore the reach of a dedicated long-lived particle project called GAZELLE. This detector would be placed $\mathcal{O}(10\,\mathrm{m})$ away from the Belle II interaction point.

For Snowmass Phase 2:
“Let a hundred thousand flowers bloom and write white papers” (T. Browder)

Snowmass Phase 3:
Workshop summer 2021 in Seattle, WA

Summary

- First LLP analysis at Belle II have started: iDM and B→KS, aiming for publication with O(100fb^{-1}) in 2021, and joining the **lifetime frontier**
- **Triggers for LLP low multiplicity states are a challenge**, since many LLP models predict low momentum V0s and/or missing energy
- **Tracking and vertexing for LLPS are challenging** since the Belle II reconstruction is not optimized for (very) off-IP tracks
- **Displaced photon identification** under study, also for L1 trigger
- **GAZELLE** is a possible new Belle II subdetector. We are currently working on a theory LLP whitepaper in the context of the US Snowmass process, including GAZELLE: **Get in touch with Susanne and/or me if you are interested to join!**

Contact

DESY.

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