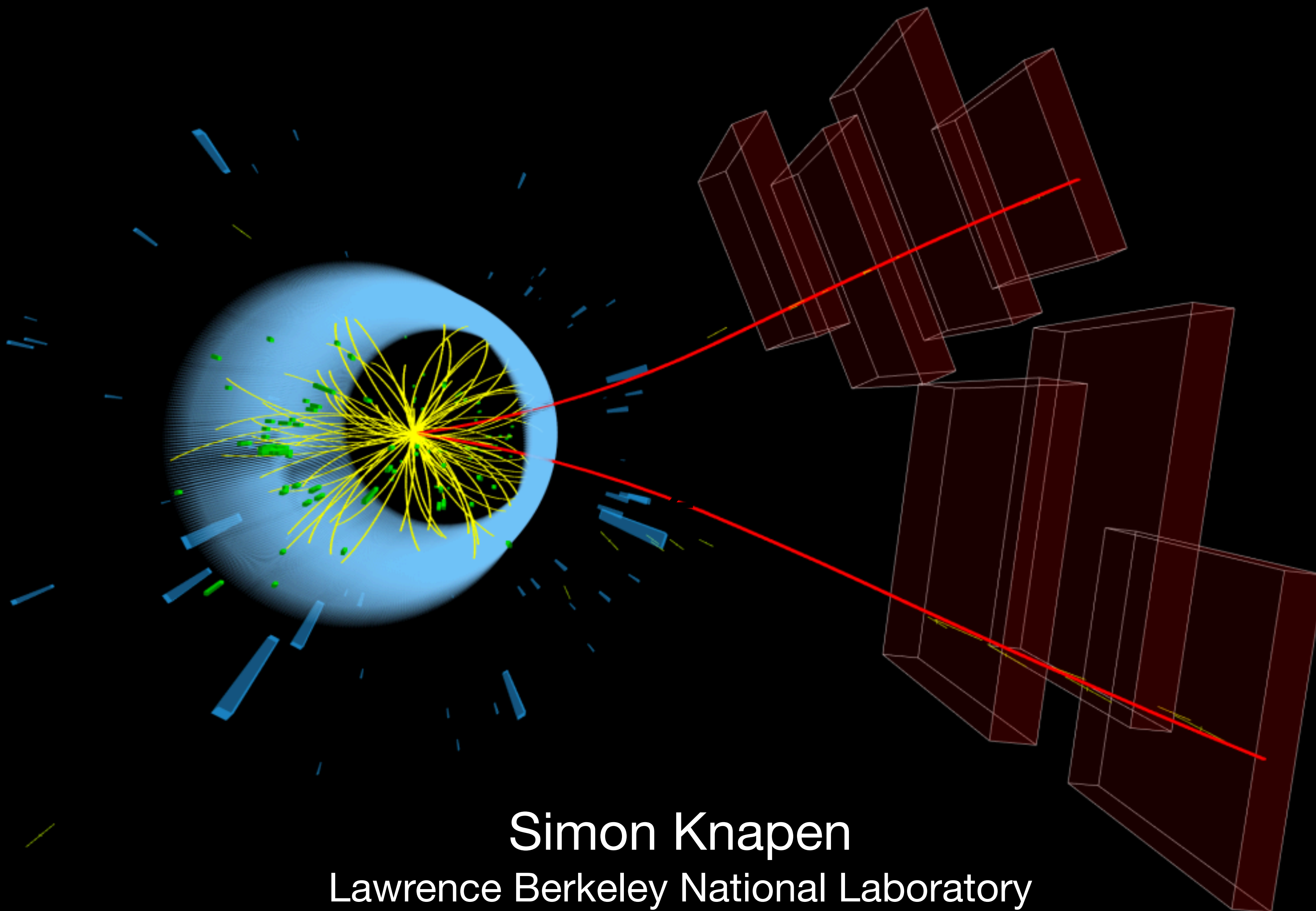
Theory for Long-lived particles at the LHC



Simon Knapen
Lawrence Berkeley National Laboratory

BERKELEY LAB

Long-lived particles at the LHC

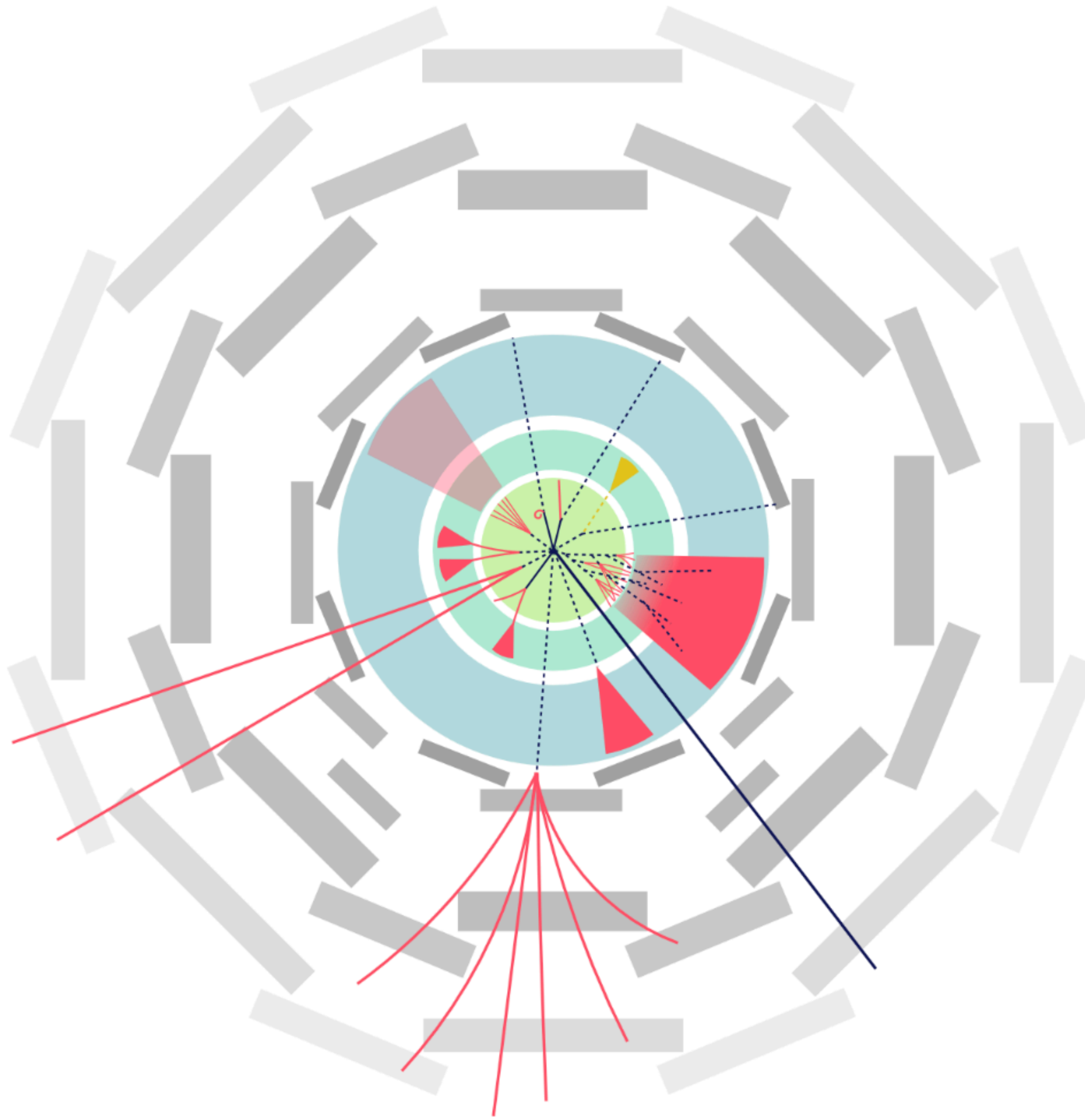


Figure by Heather Russell

Rich phenomenology but very challenging

Need extremely clever experimentalists + a LOT of work

So why bother?

Pragmatic reasons:

Displaced signatures not visible without dedicated reconstruction

Gives new handles to reject backgrounds

→ A lot of discovery potential missed if we don't search for LLPs!

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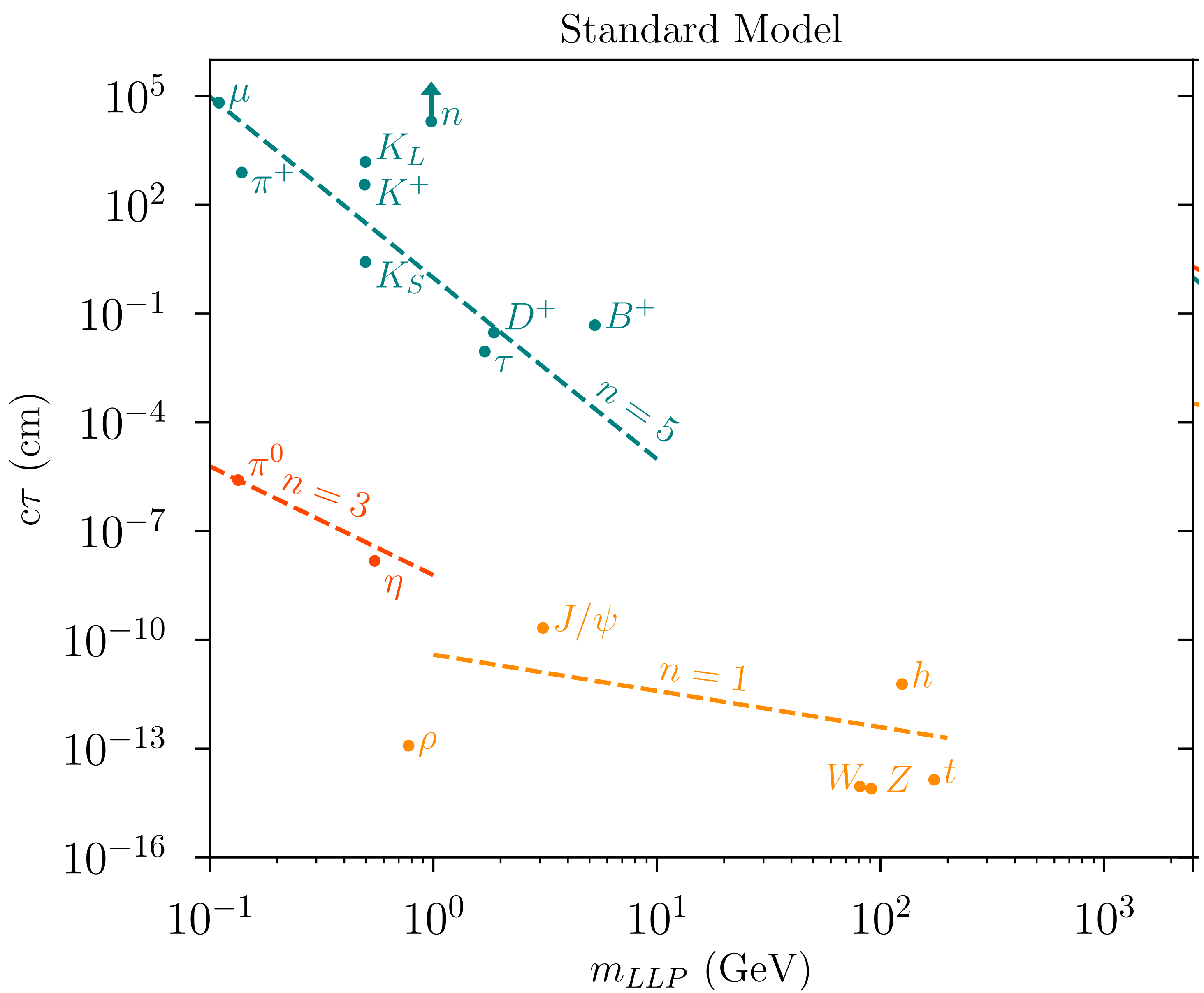
Theory priors:

Displaced decays are generic for low mass extensions of the SM

Displaced decay arise when there is a hierarchy of scales or approximate symmetry

LLP's in the Standard Model



Can be sorted in equivalence classes

For example:

$$\Gamma \sim \frac{|V_{CKM}|^2}{64\pi^2} \frac{m_{LLP}^5}{m_W^4}$$

Long lifetime due to:

- Mass hierarchy (offshell W)
- small parameter (V_{CKM})

SK, S. Lowette: arXiv 2212.03883
(hopefully) pedagogical review on LLPs

High mass example: Split SUSY

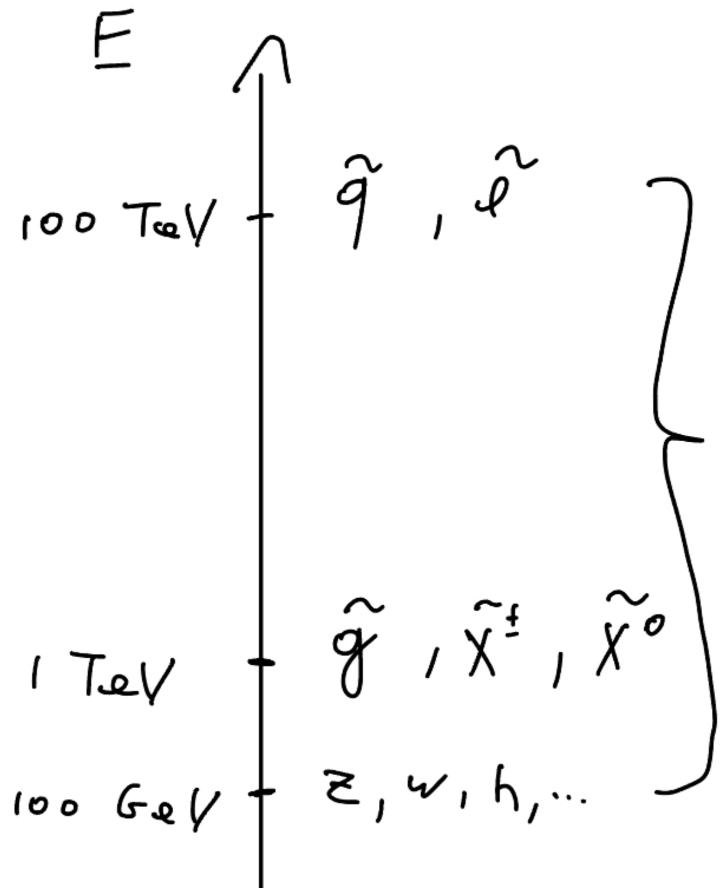
GRAND UNIFICATION ✓

WIMP DARK MATTER ✓

NO FLAVOR / CP PROBLEMS ✓

FINE TUNING NEEDED ✗

High mass example: Split SUSY



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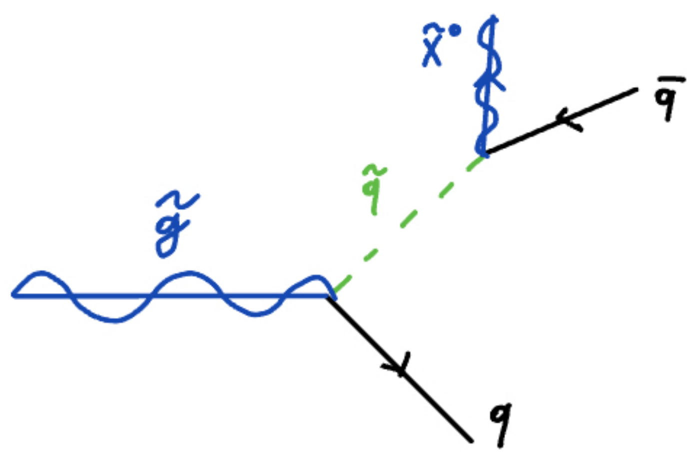
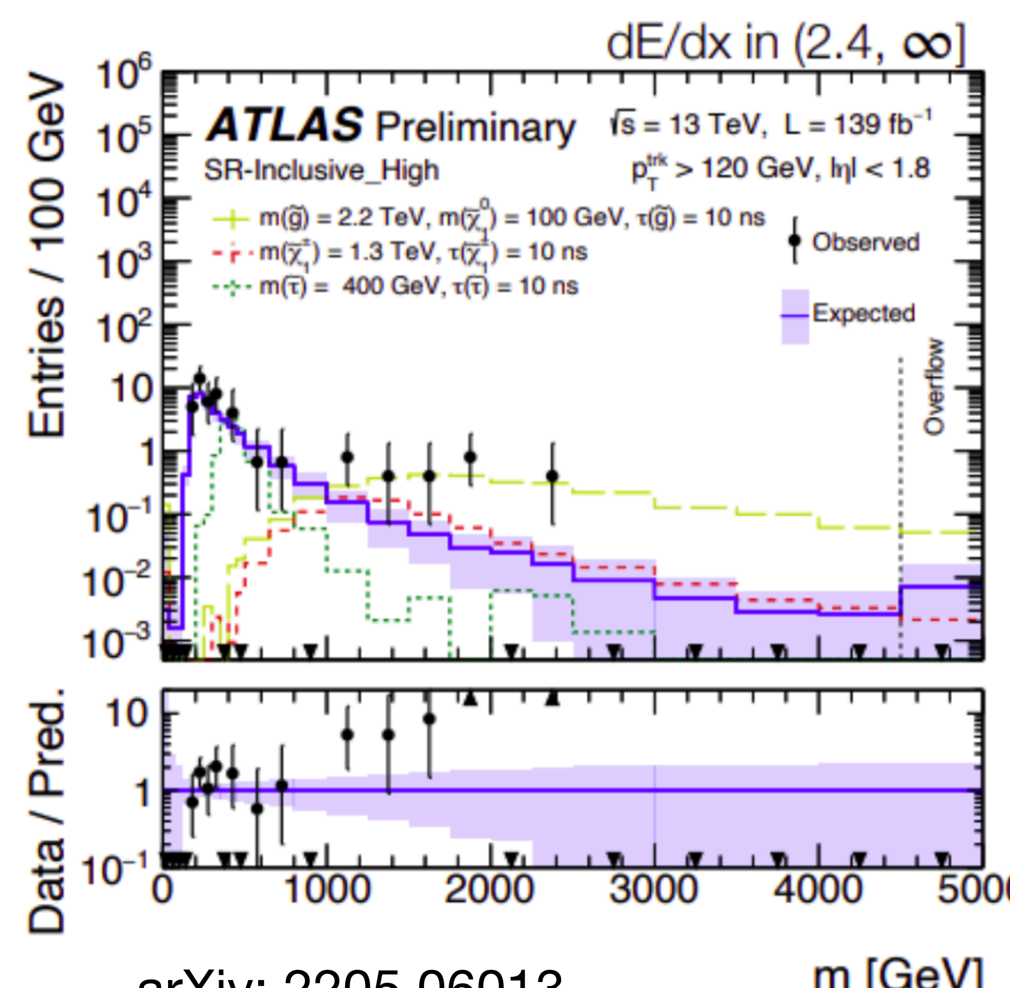


$$\Gamma \sim \frac{m_{\tilde g}^5}{m_{\tilde q}^4}$$

→



arXiv: 2205.06013

Gluino can easily be long-lived

Low mass example: dark Higgs

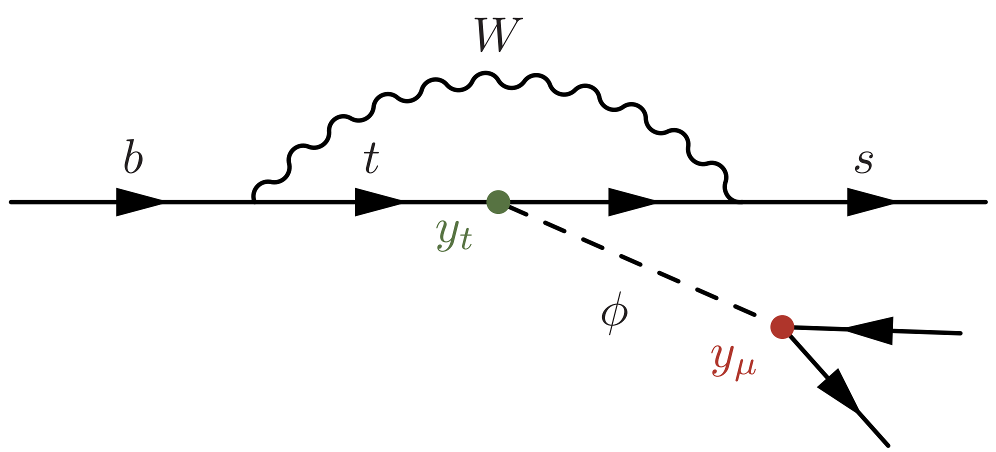
Scalar singlet extension of Higgs sector: $\mu\,\phi H^\dagger H \quad \rightarrow \quad s_\theta y_f \phi \bar{f} f \qquad (s_\theta \ll 1)$

(Most minimal extension of the Standard Model)

<u>Production:</u> (for $m_\phi < m_B - m_K$)

$$\mathrm{Br}[B \rightarrow X_s \phi] \approx 6\, s_\theta^2\, (1 - m_\phi^2/m_B^2)^2$$

R. S. Willey and H. L. Yu (1982)
R. Chivukula and A. V. Manohar (1988)
B. Grinstein, L. J. Hall, and L. Randal (1988)
B. Batell, M. Pospelov, A. Ritz (0911.4938)
…



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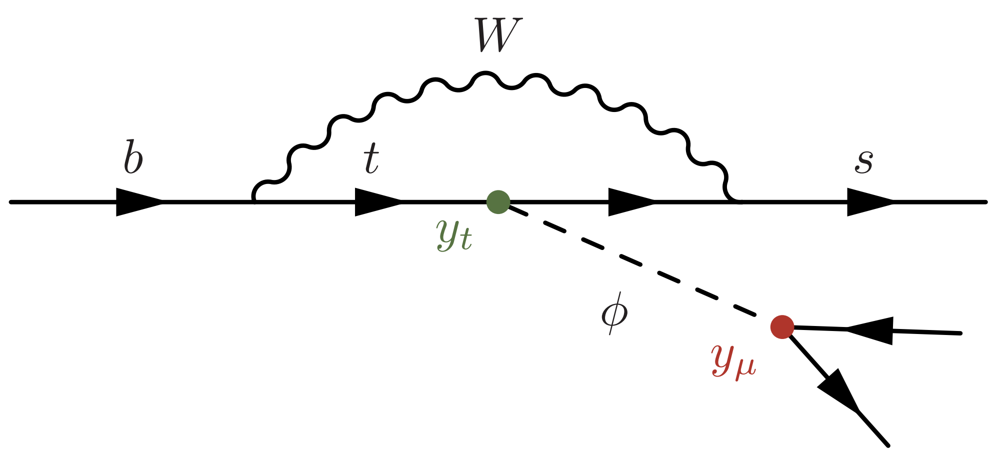
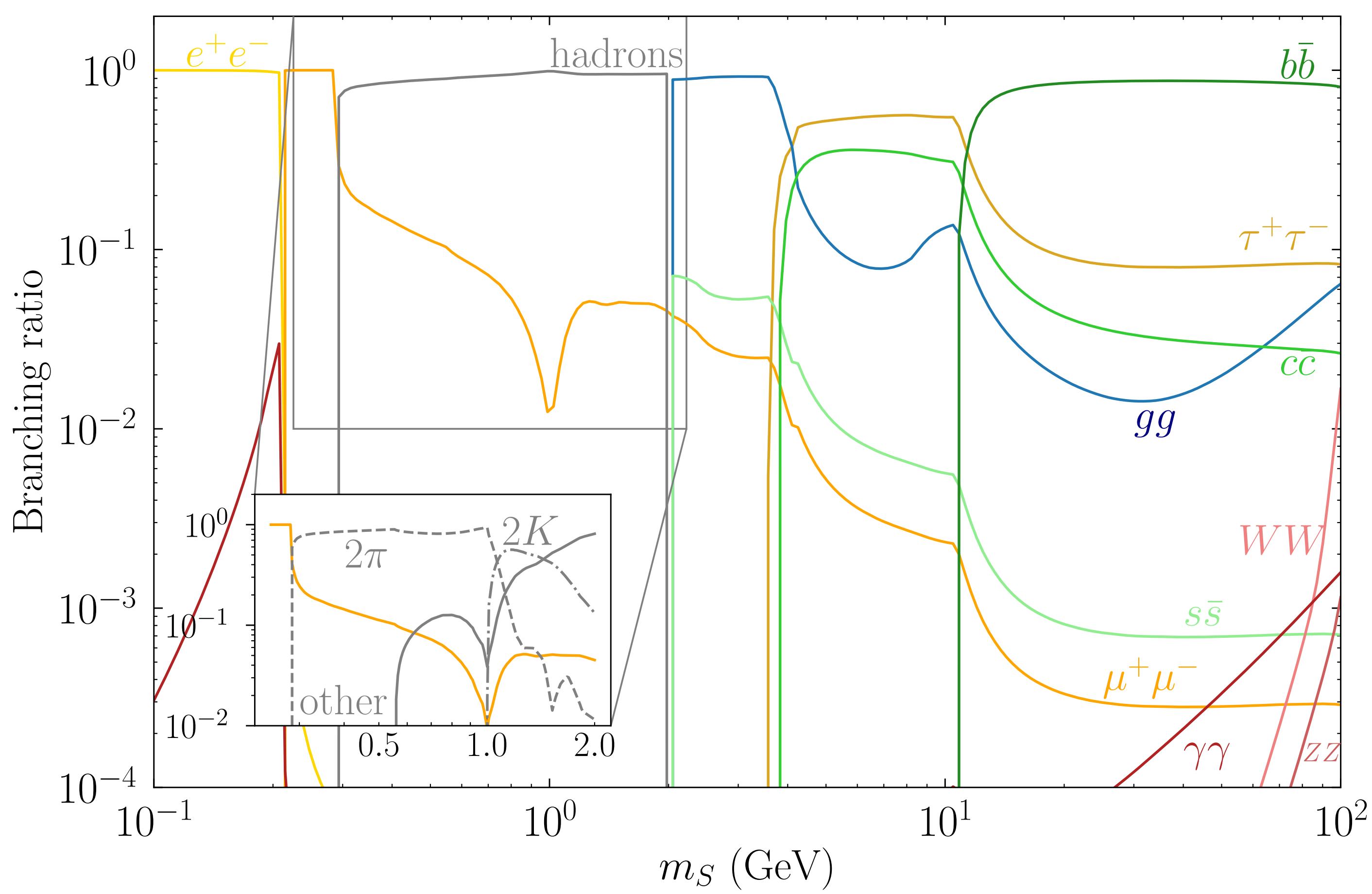


Decay rate suppressed by small Yukawa couplings

↓

$c\tau \gtrsim 0.1$ cm for $m_S \lesssim 5$ GeV



Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864

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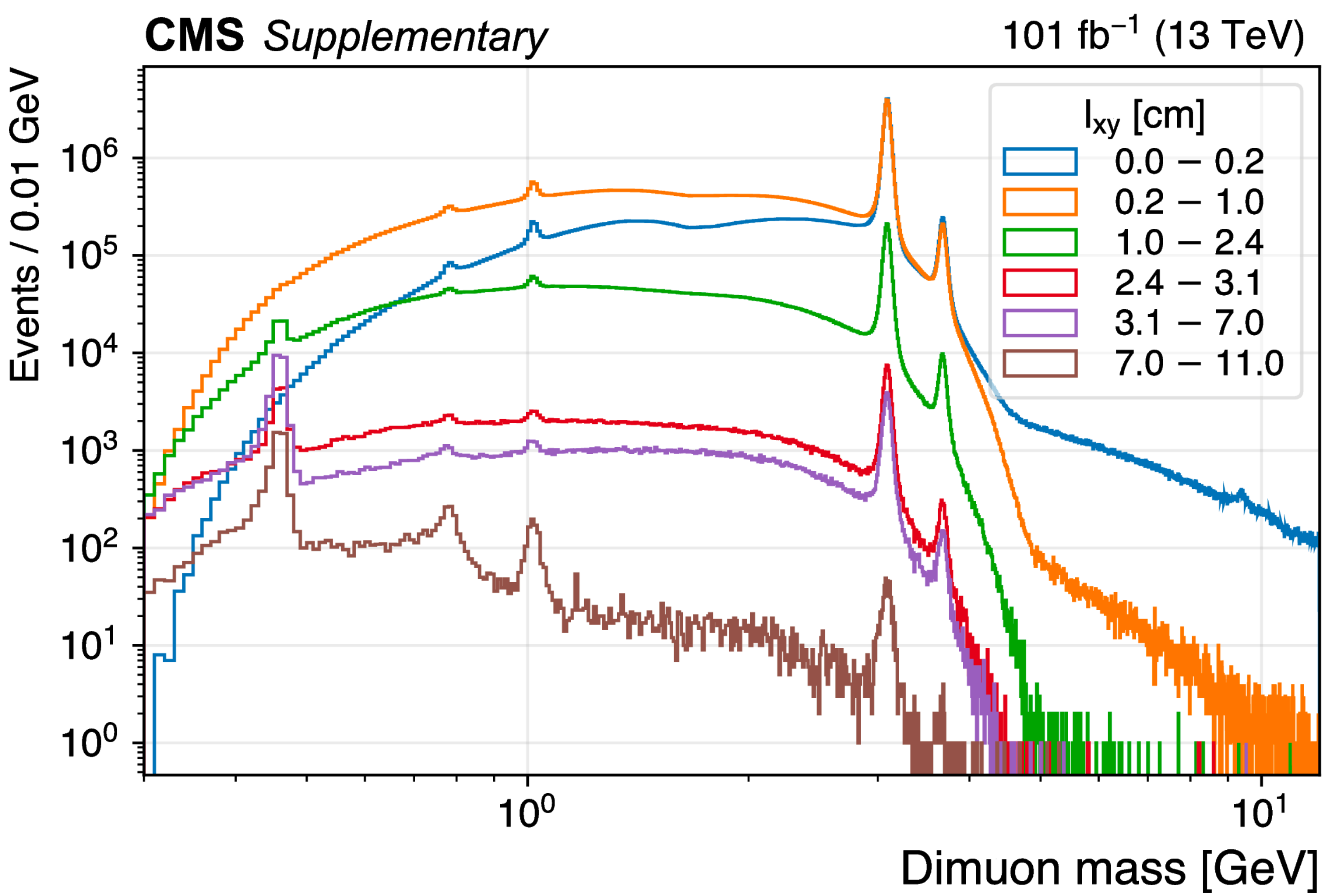
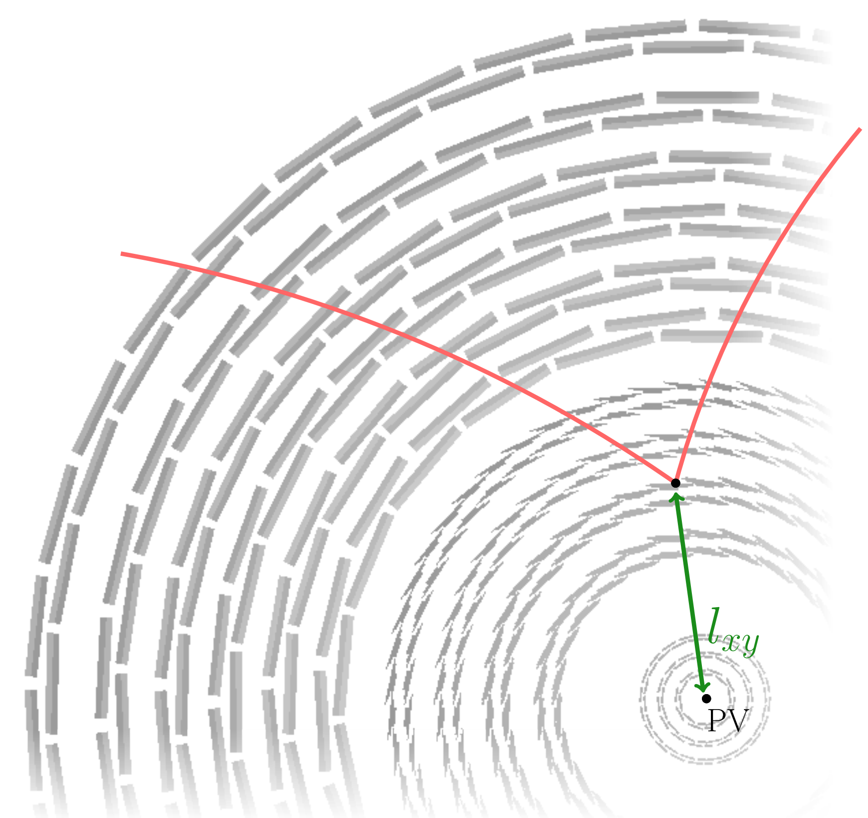




- Very low threshold! $p_{T_{1,2}}^{\mu} > 3$ GeV
- Includes isolation information
- Includes displacement information

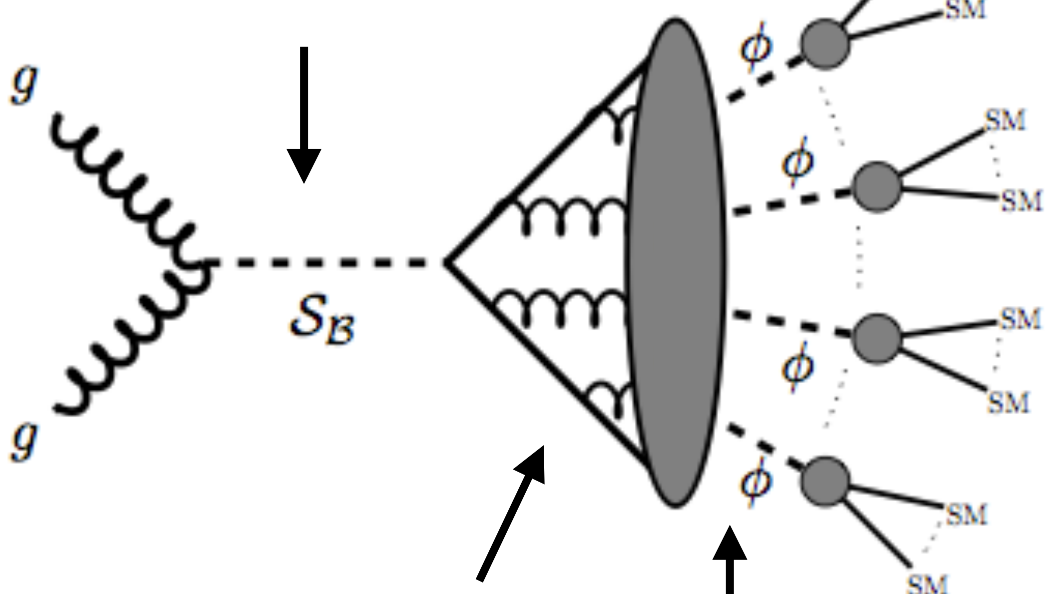
Until this result, this was LHCb territory

CMS arXiv: 2112.13769

Hidden valleys

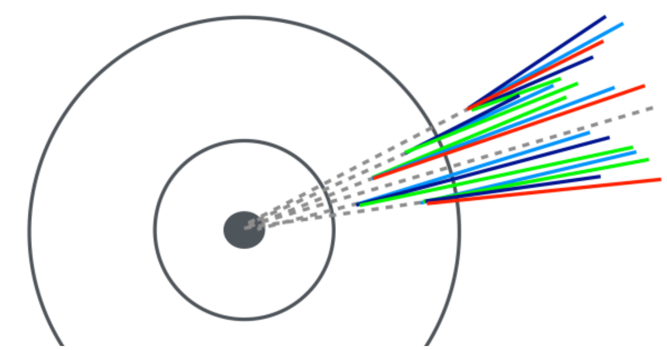
decays to SM
often displaced

Some heavy mediator
e.g. Higgs



dark parton
shower

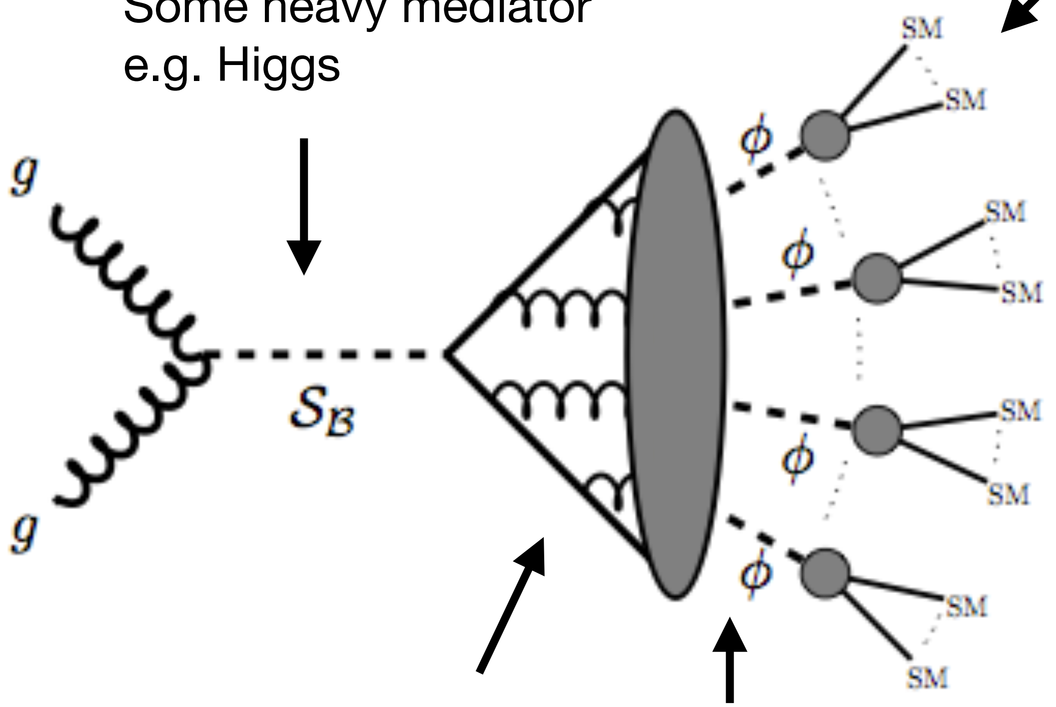
dark
hadronization

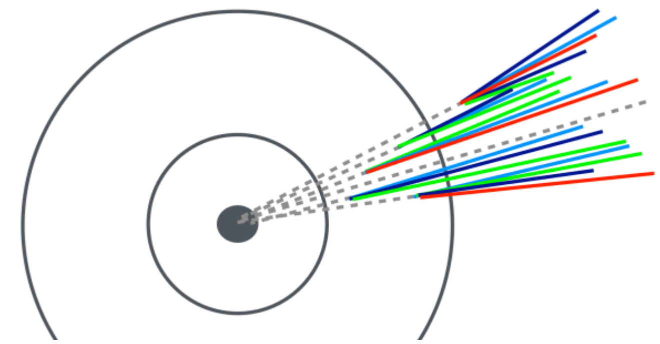


“dark showers”
Complicated final state
with multiple vertices

M. Strassler, K. Zurek: arXiv 0604261
Snowmass: arXiv 2203.09503

Hidden valleys





"dark showers"
Complicated final state
with multiple vertices

This stuff can show up in

- Neutral Naturalness models (N. Craig, SK, P. Longhi 1410.6808, N. Craig et. al. 1501.05310, ….)
- Dark matter models (e.g. asymmetric DM, strongly interacting dark matter, composite dark matter,…)

M. Strassler, K. Zurek: arXiv 0604261
Snowmass: arXiv 2203.09503

Hidden meson lifetimes

Very difficult to make generic statements about multiplicity, pT spectra etc: hidden valley hadronization is not understood

But we *can* reliably predict the *minimal* dark meson lifetime for the most motivated decay portals

SK, J. Shelton, D. Xu: arXiv 2112.07720

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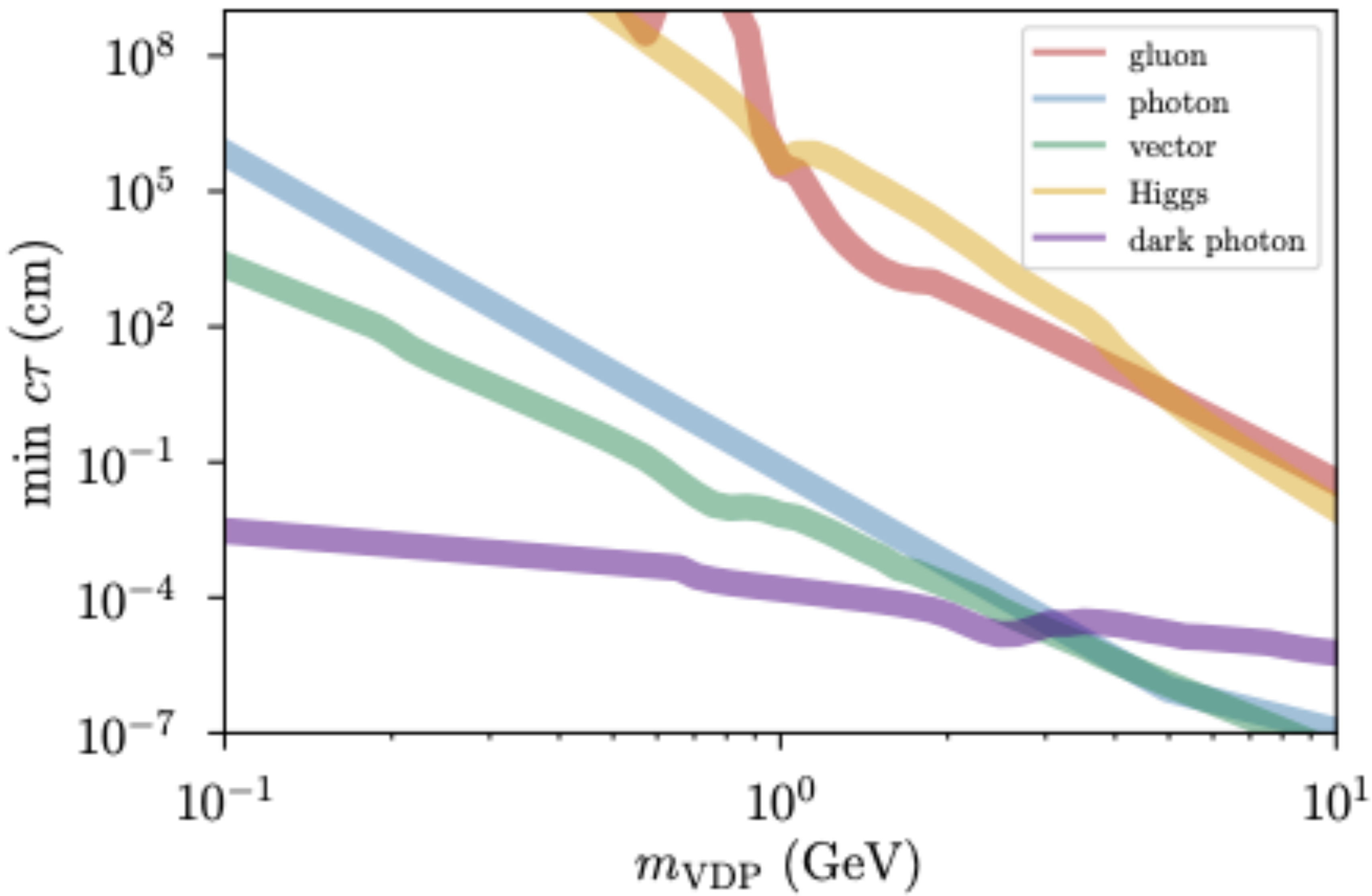

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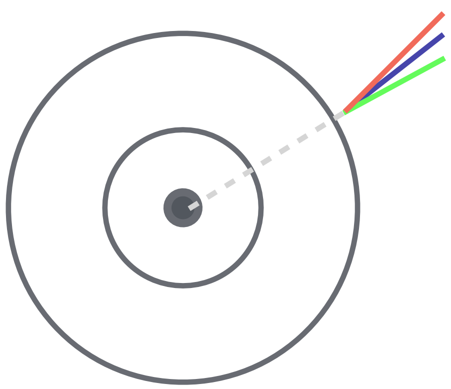
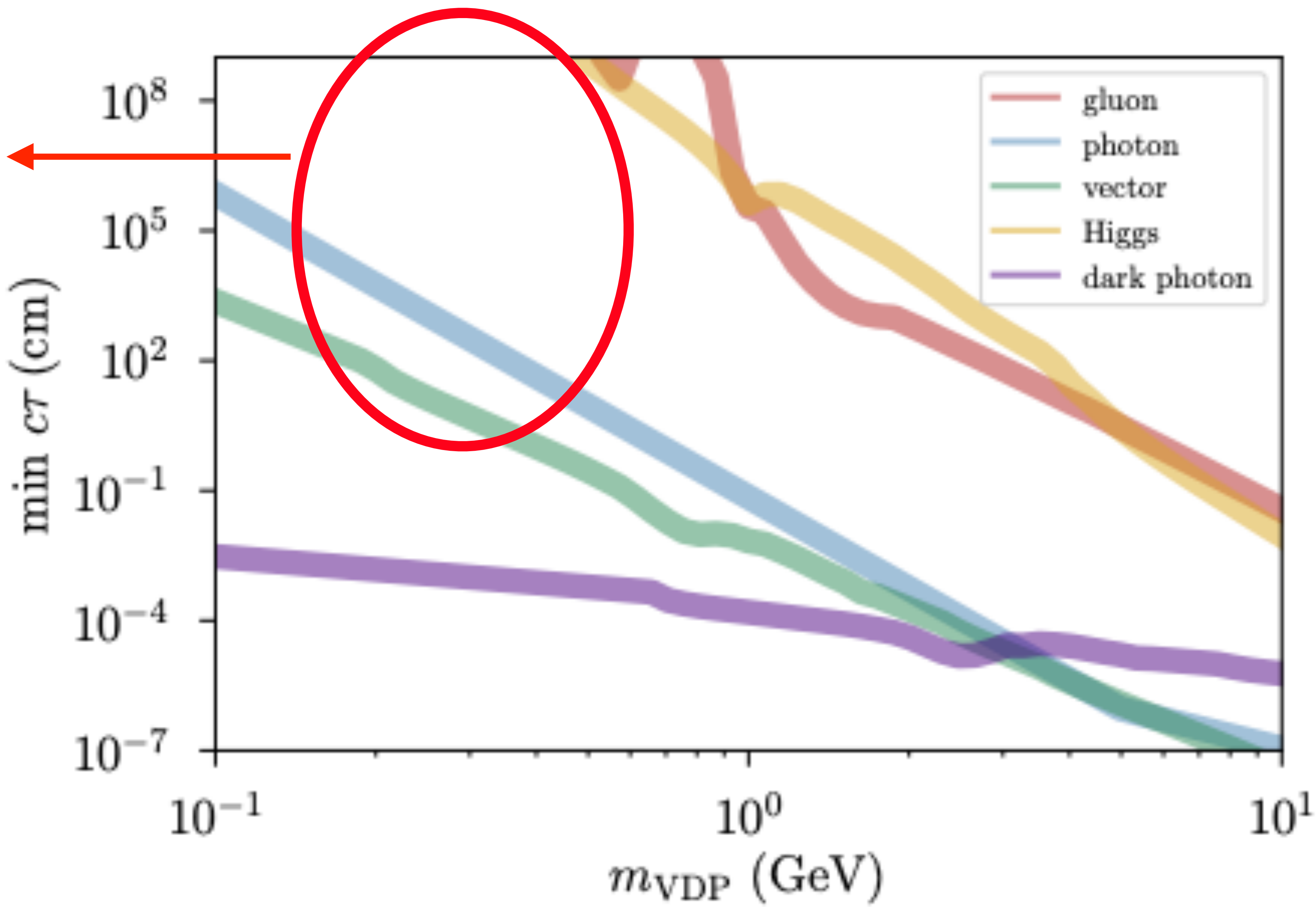


Cover with searches for 1 displaced vertex



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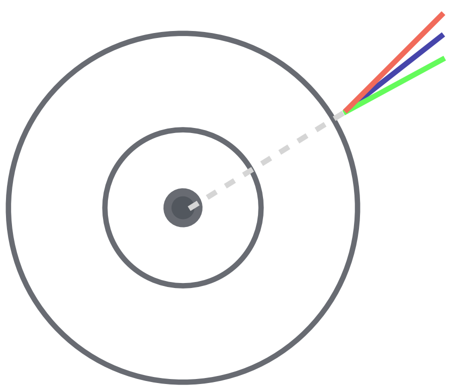

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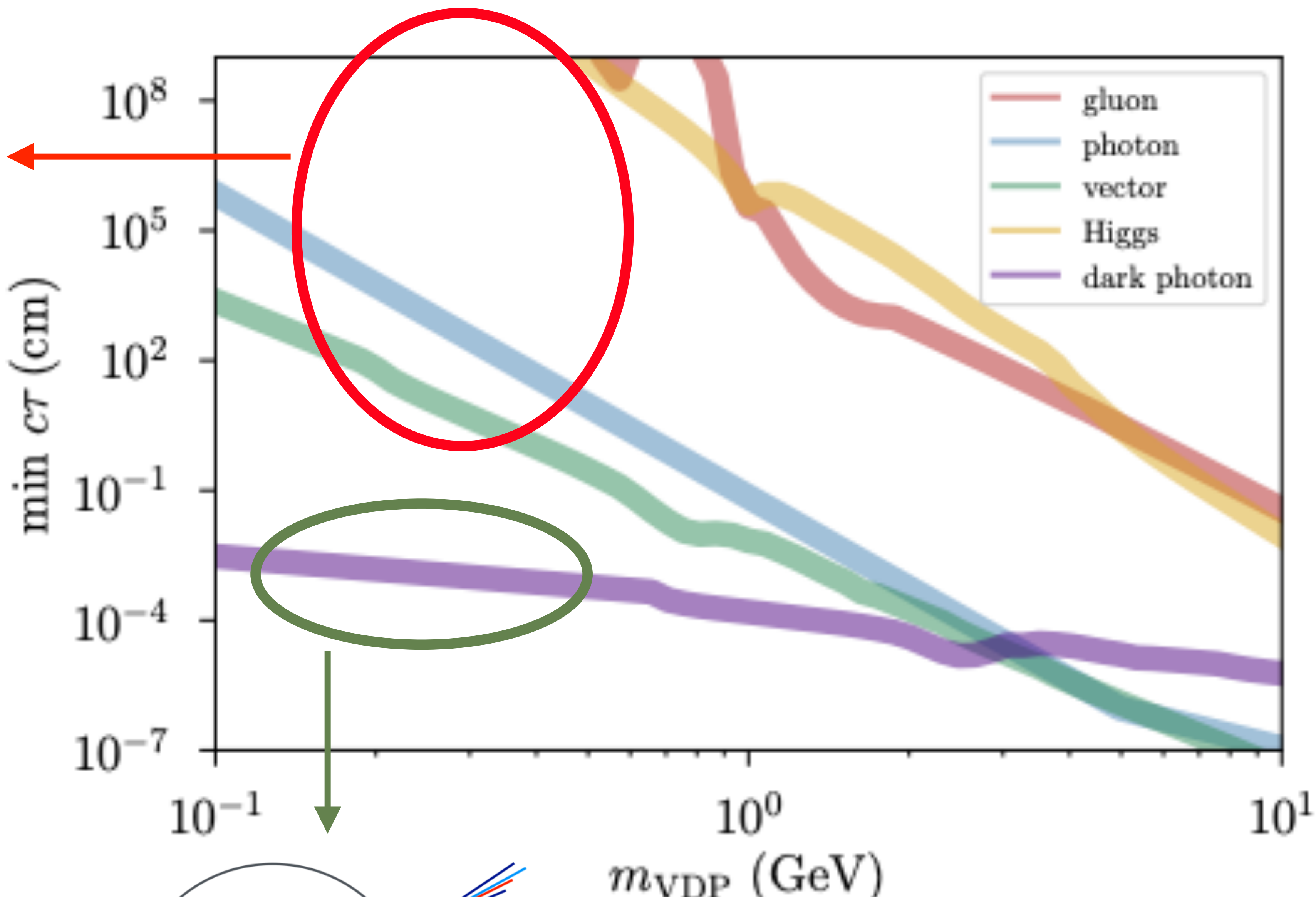
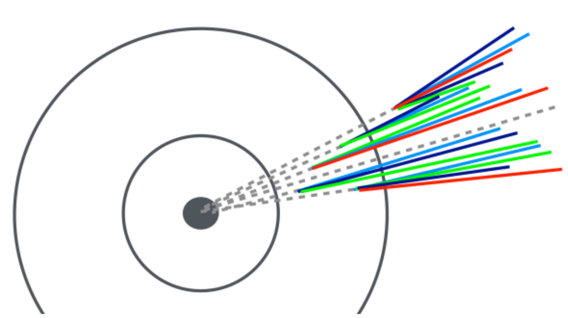


Special techniques needed



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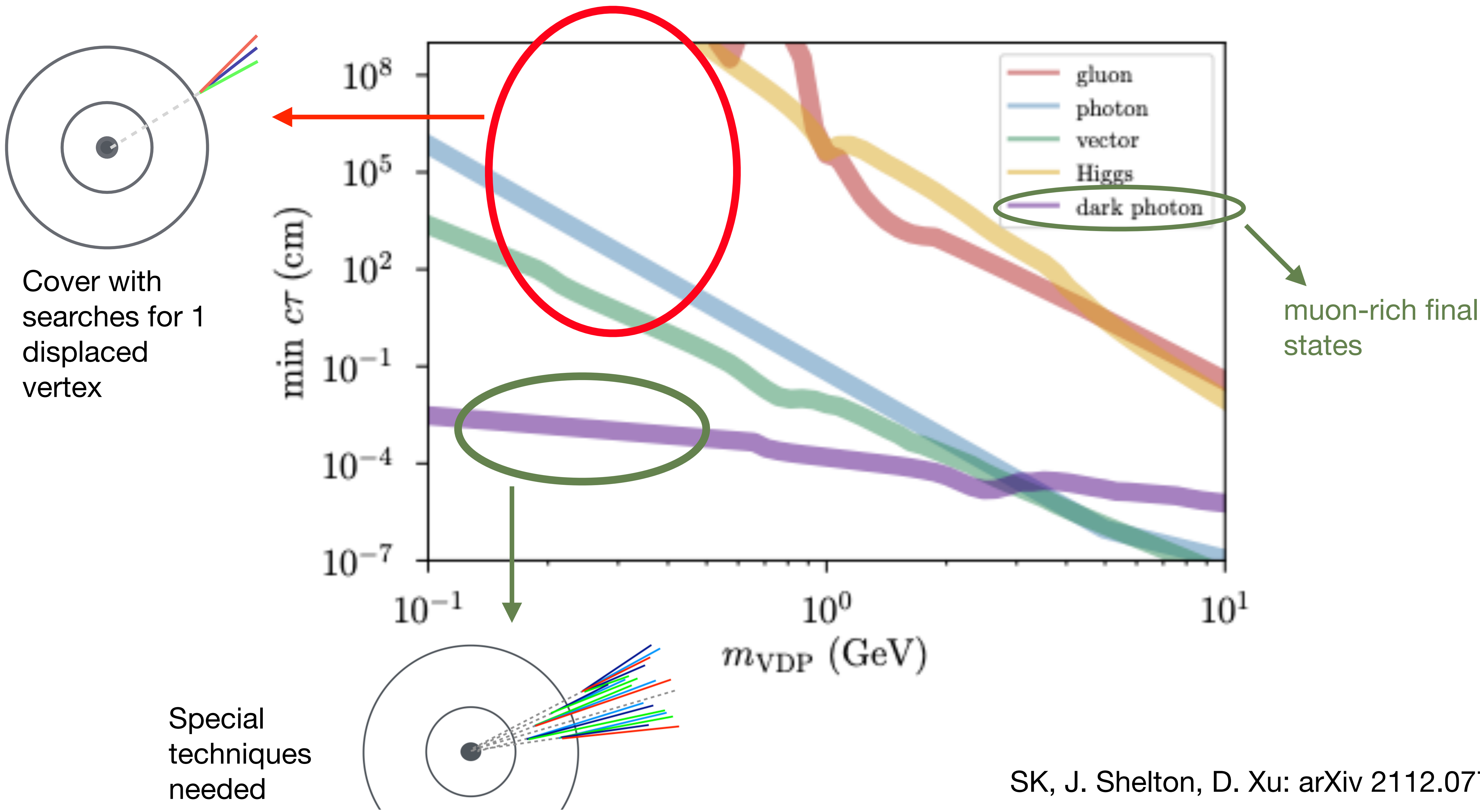


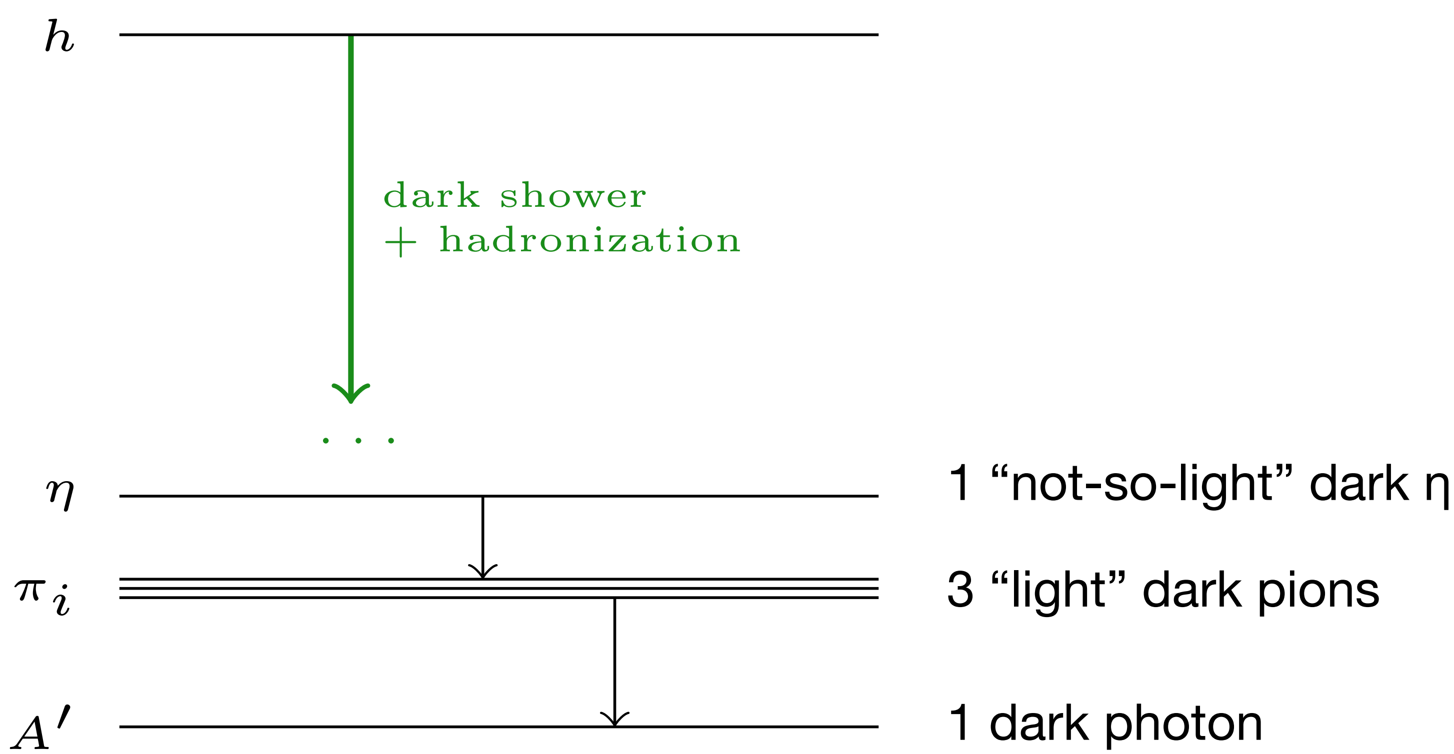
SK, J. Shelton, D. Xu: arXiv 2112.07720

Example model with dark photon portal

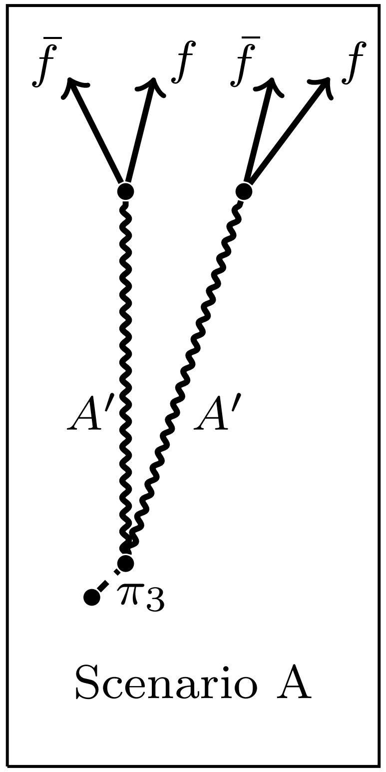
Consider a dark QCD with two flavors ($N_f = 2$)
+ light, elementary dark photon (A')

Dark mesons produce dark photons, which decay to the SM

Production through exotic decay of SM Higgs



Example:

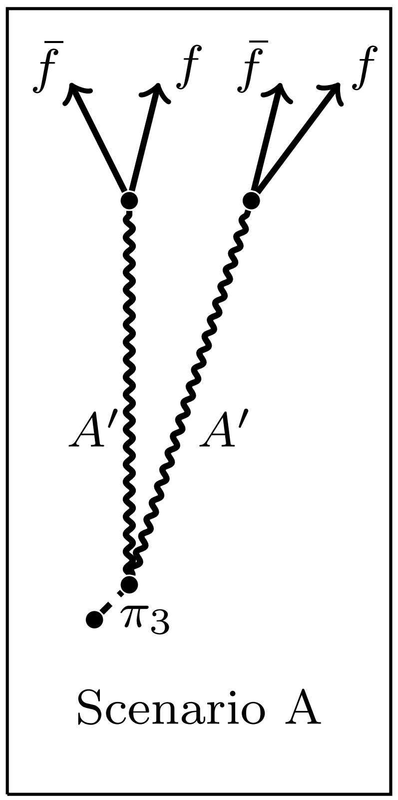


Produces several dark photons per event

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

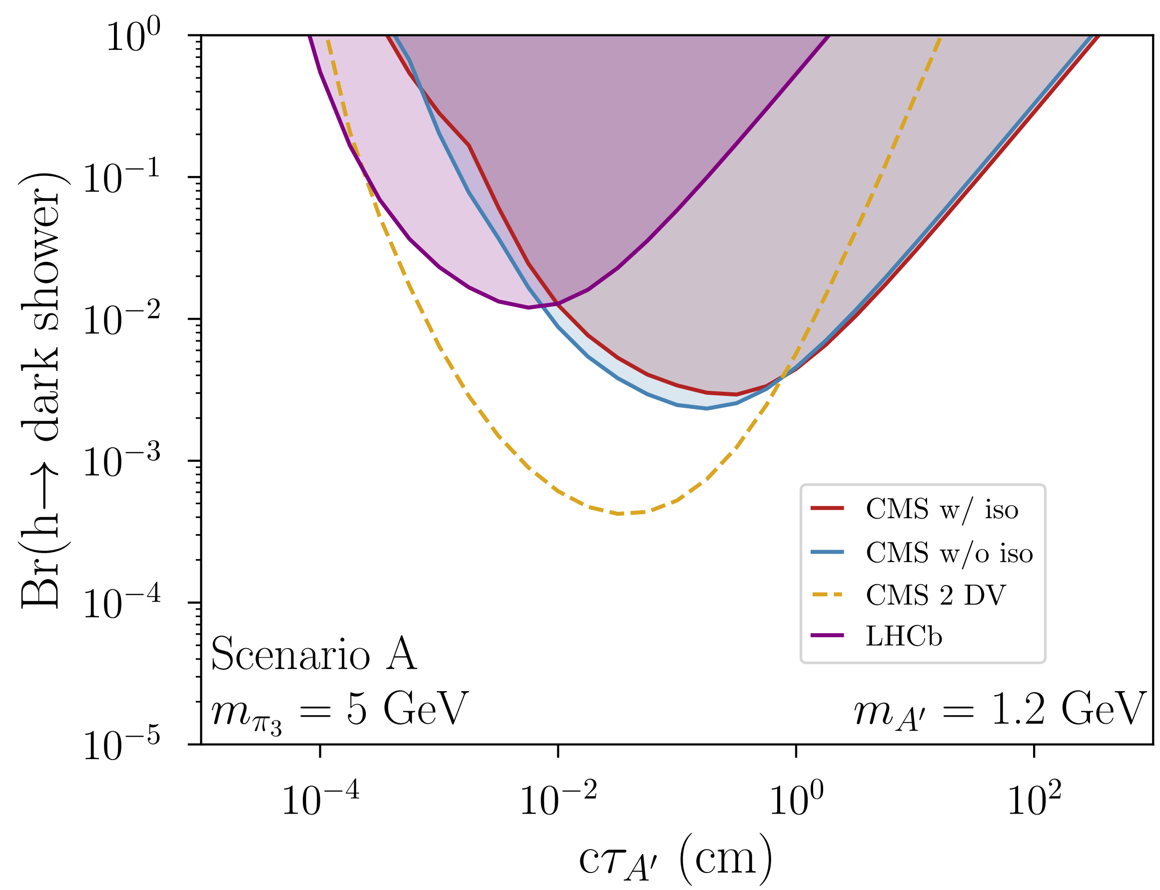
Existing sensitivity

π decays prompt
A' long-lived



Resonant dimuons point to beamline

CMS and LHCb searches directly apply
→ we can perform a recast to compare them

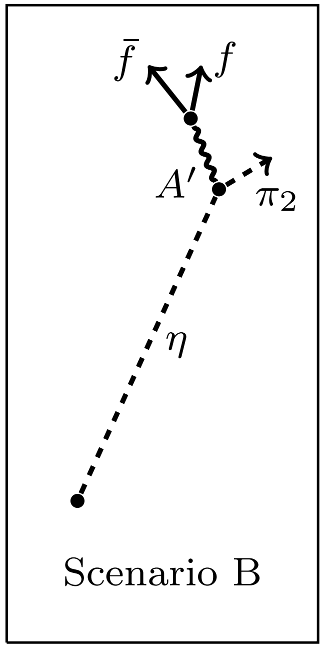


LHCb and CMS have complimentary reach
(Plot made before publication of CMS prompt search)

CMS reach may be enhanced by requiring 2 dimuon pairs per event

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

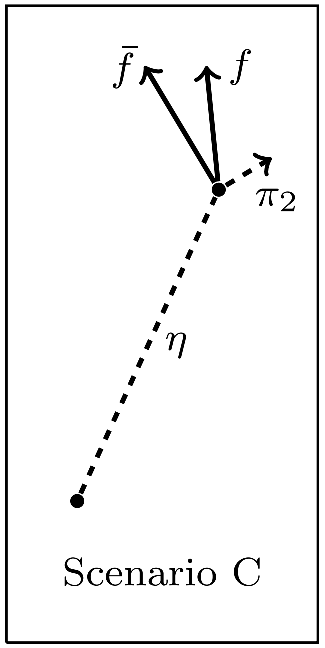
New extensions of the scouting analysis



A' off-shell
η long-lived & 3 body

→ Resonant dimuons do not point to beamline

Relaxing pointing cut would increase signal efficiency x 10, but let in more background



A' decays prompt
η long-lived

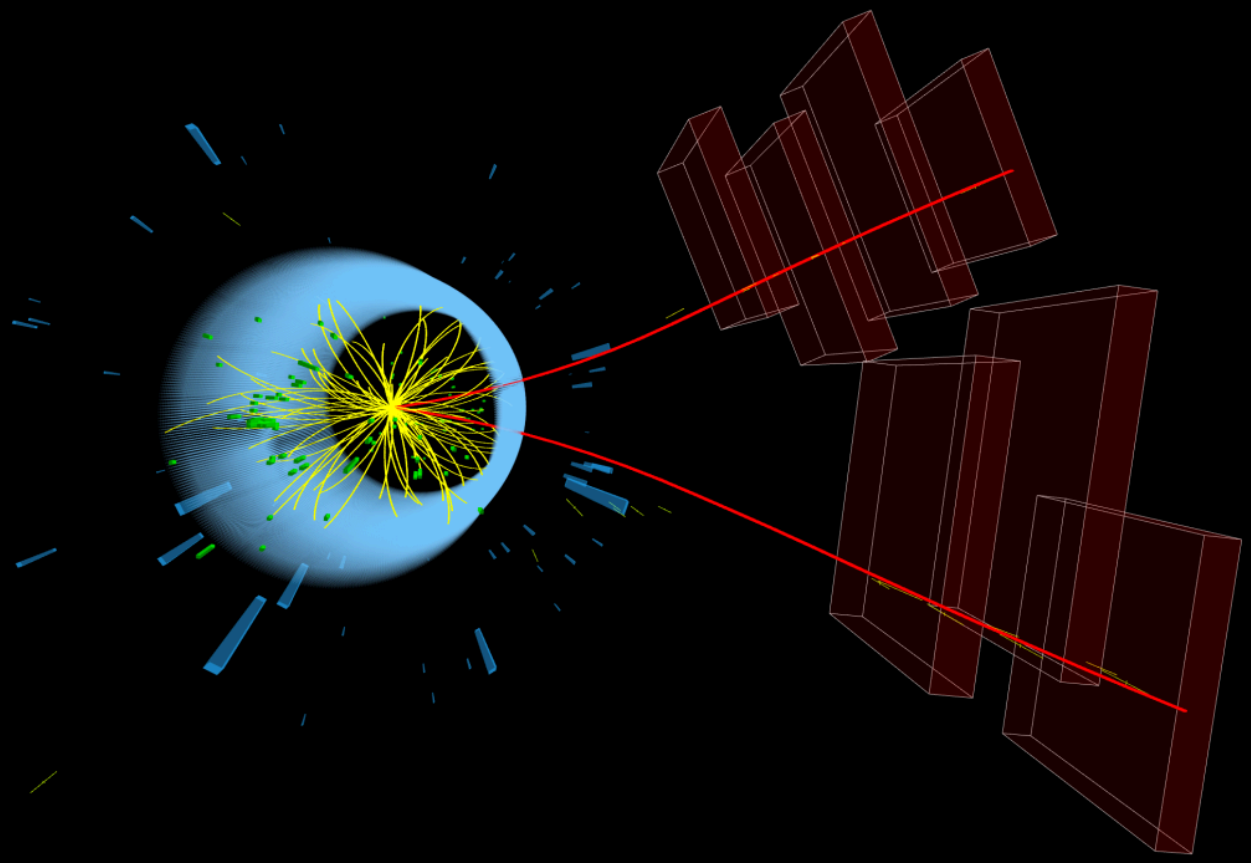
→ Non-resonant dimuons do not point to beamline

Look for an edge in the dimuon mass spectrum

Likely difficult due to backgrounds

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

Summary

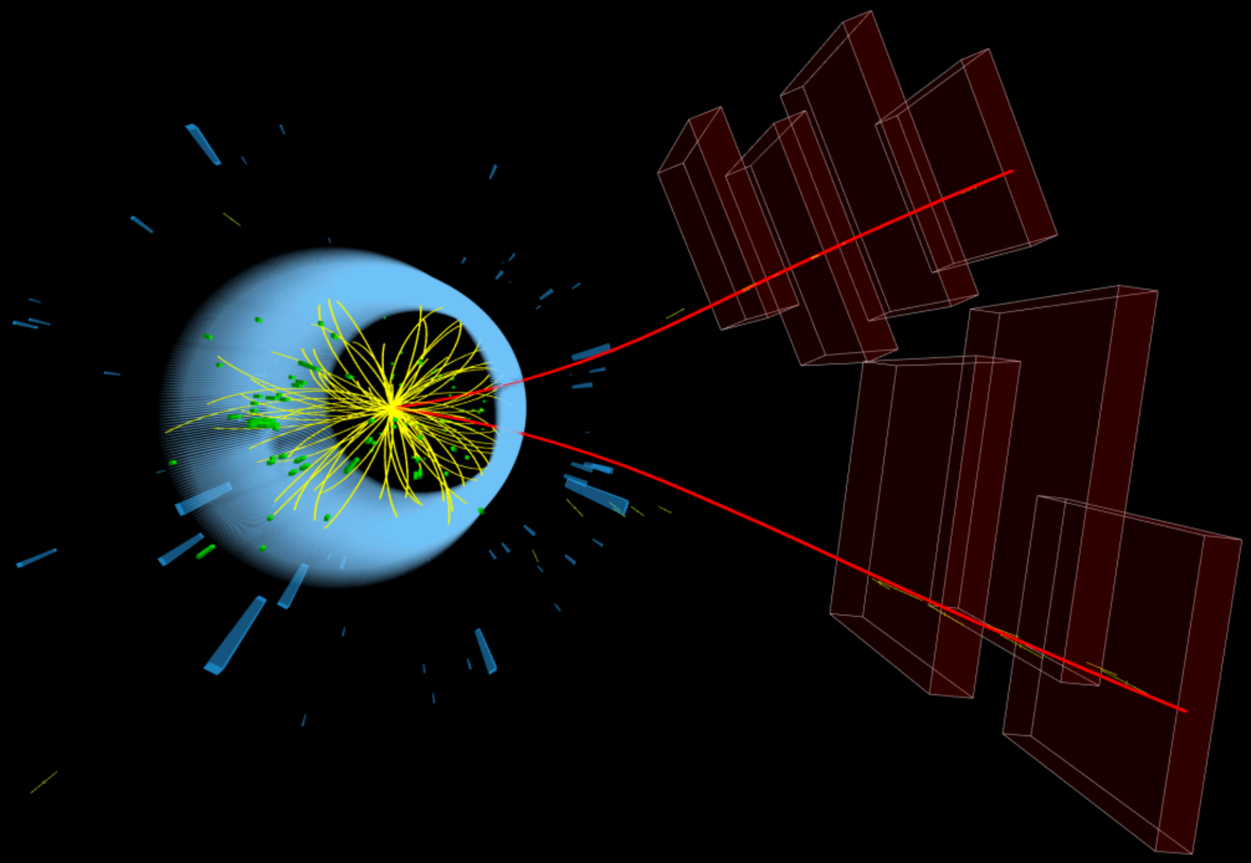


Long-lived particles are theoretically well motivated and exciting experimental opportunities

Searches are very challenging, pushing experimentalists to be creative

Often backgrounds can be reduces to < 1, leading to favorable scaling with luminosity

Summary



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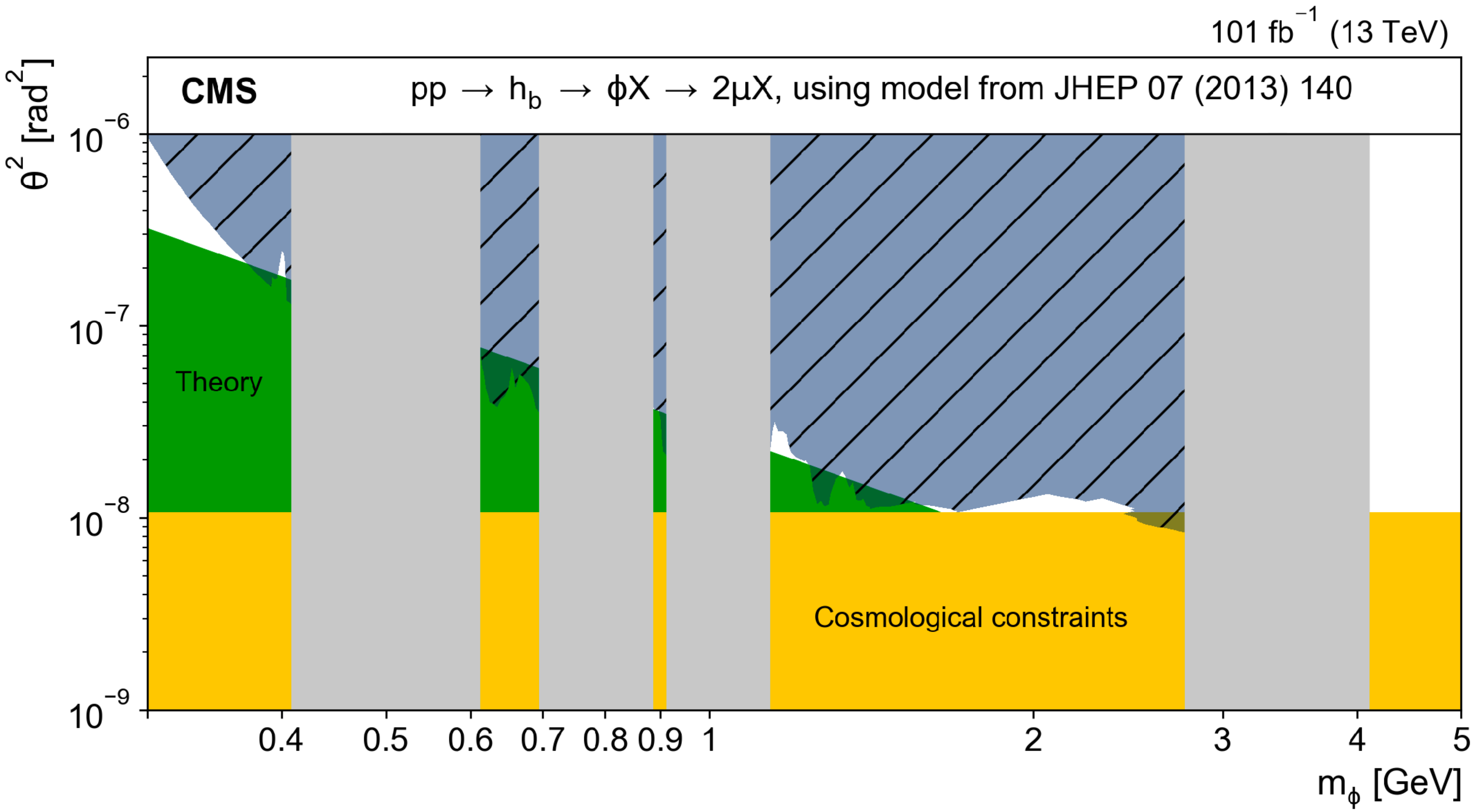
Often backgrounds can be reduces to < 1, leading to favorable scaling with luminosity

Room for new creative approaches especially for low mass LLP’s

- New scouting/trigger strategies
- Auxiliary experiments (CODEX-b, Miliqan, FASER, etc)
- Complementarity with meson factories / beam dumps

BSM example 2: dark Higgs

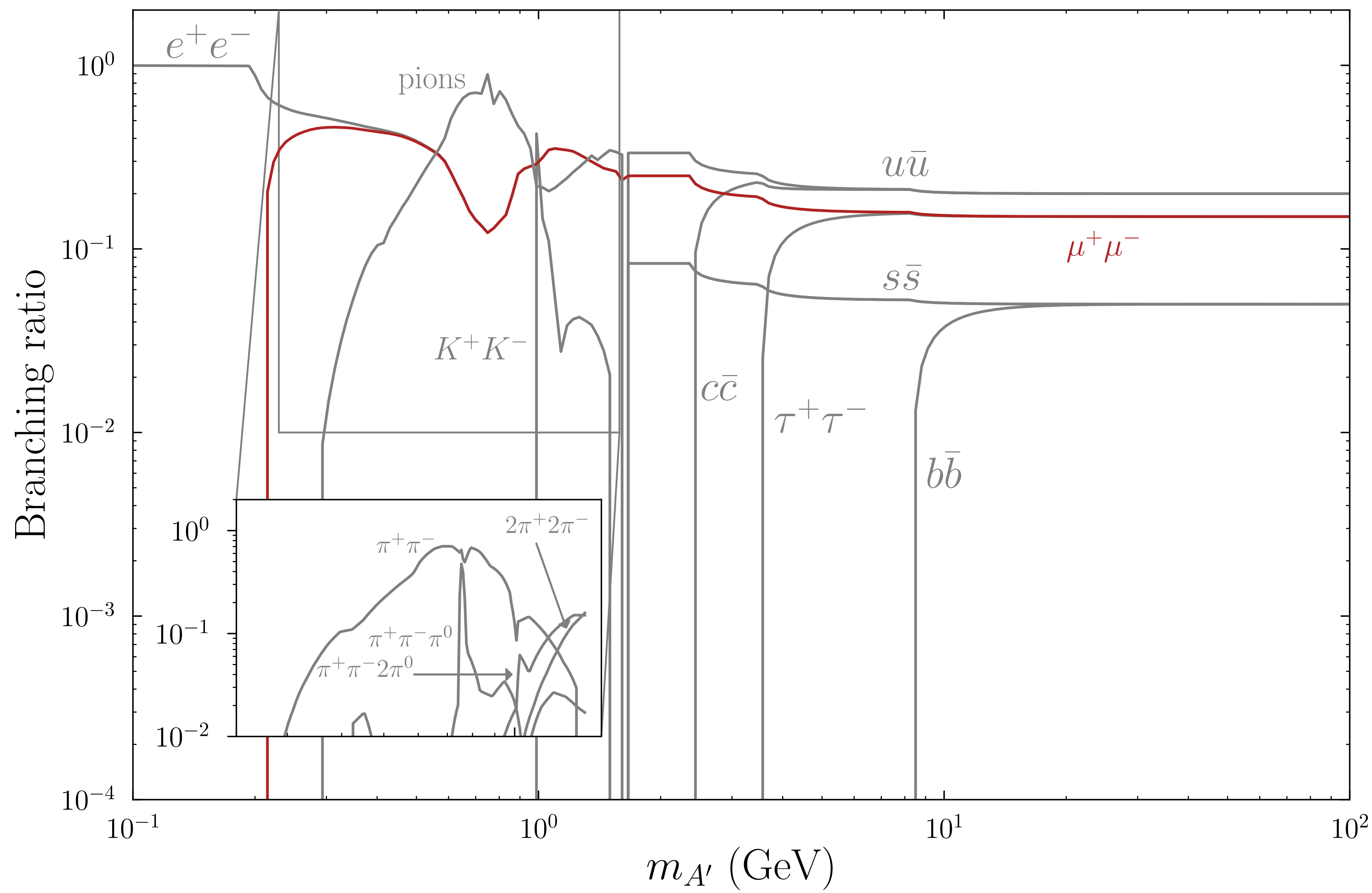
CMS search for ultra soft dimuon pairs using “data scouting”



Write out only a small fraction of the whole event (muon 4-vectors) to allow for lower trigger thresholds

arXiv: 2112.13769

Dark photon branching ratios

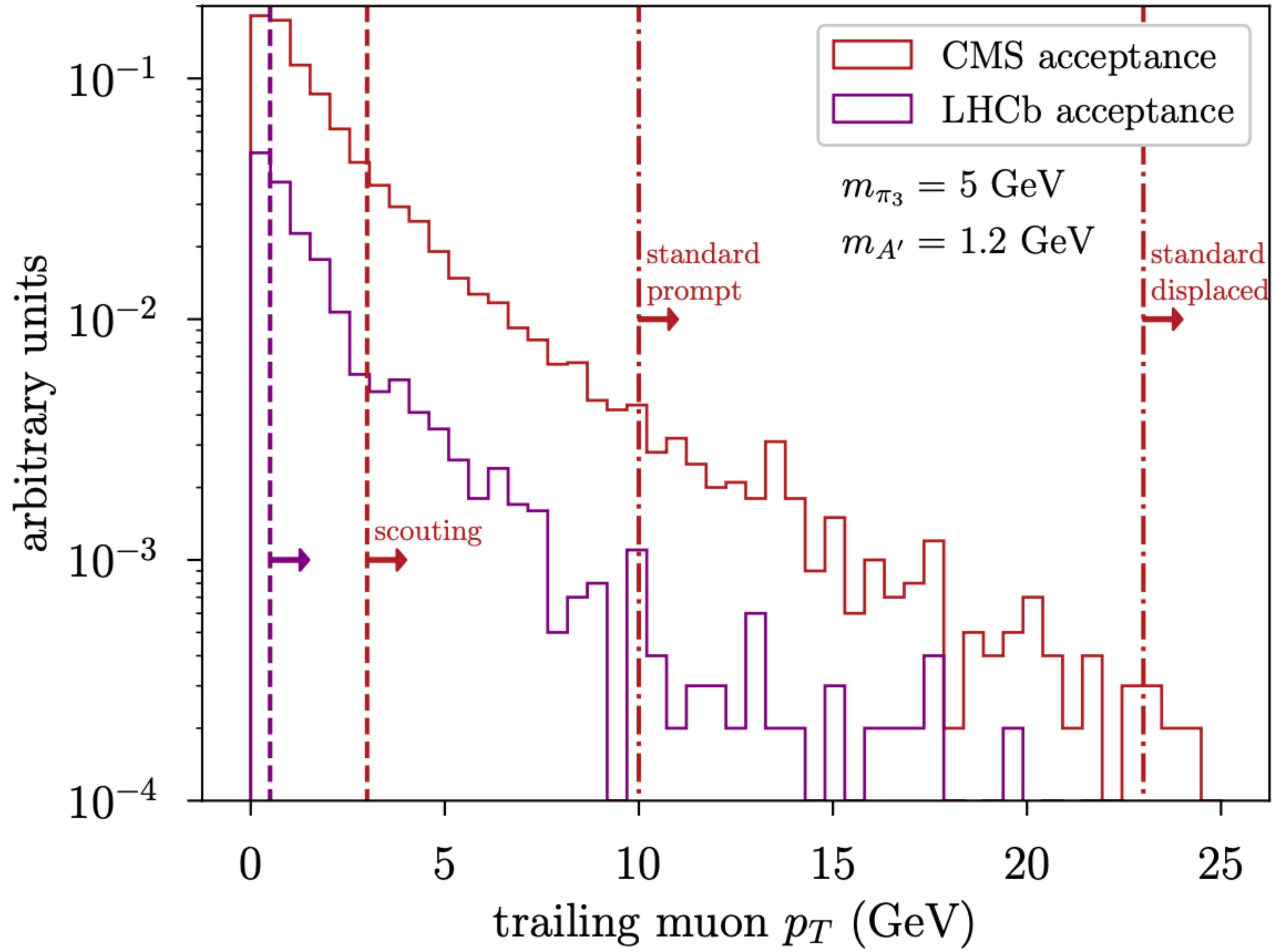


O(1) branching ratio to muons, much higher than for the scalar mixing with Higgs

Ideal for low pT muon search

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

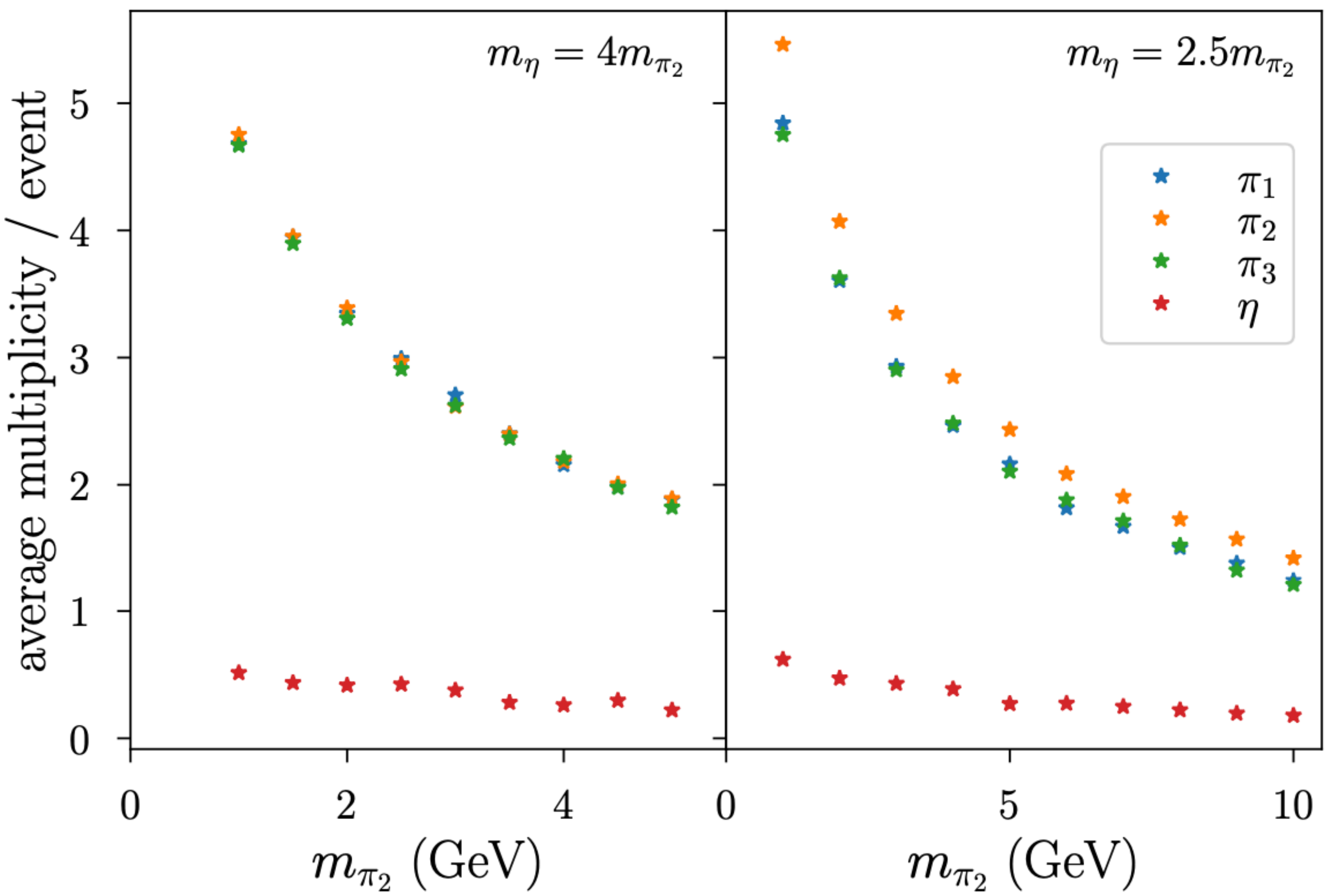
Why do we need scouting?



muon pT is very low, and standard trigger selections are very costly, especially for displaced muons

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

Dark meson multiplicity



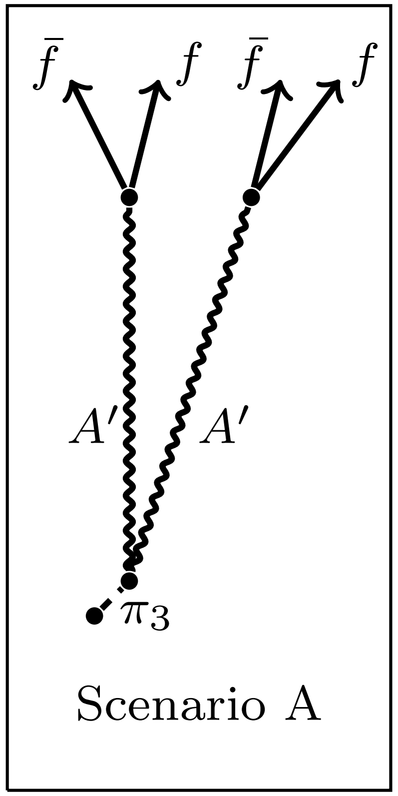
O(few) dark pions / event for an exotic Higgs decay

It appears to be difficult to get this to be much higher in most perturbative showers, with current hadronization models

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

Three scenarios

π decays prompt
A' long-lived



Resonant dimuons point to beamline

CMS requires pointing to reduce background from fake displaced vertices

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

Three scenarios

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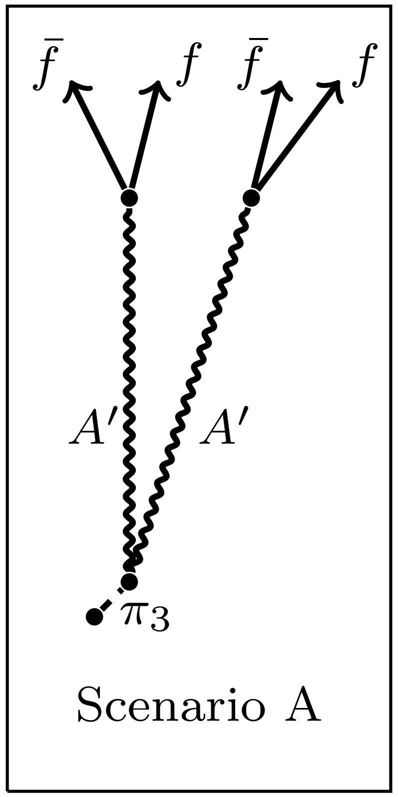

Resonant dimuons
point to beamline

A’ decays prompt
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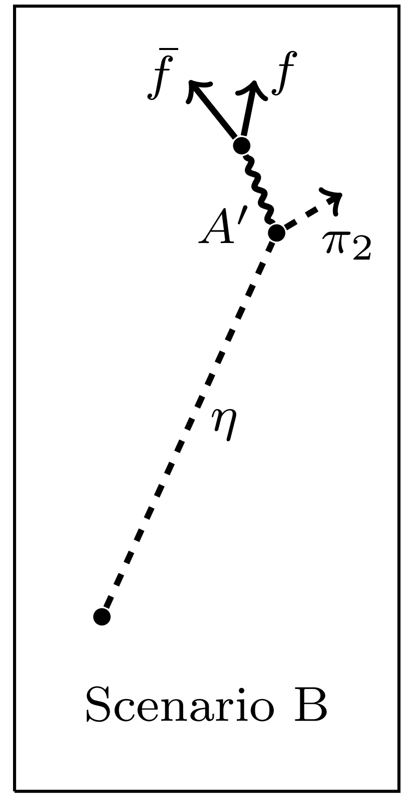

Resonant dimuons
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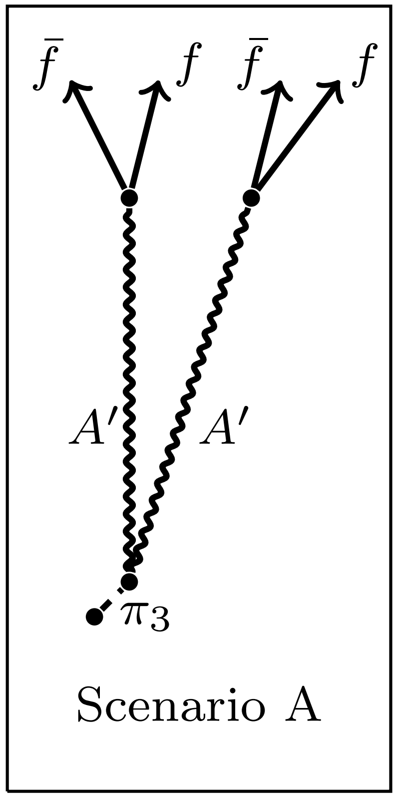

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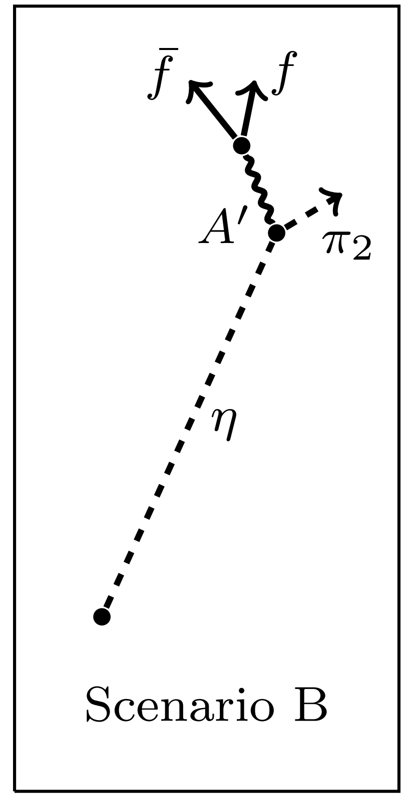
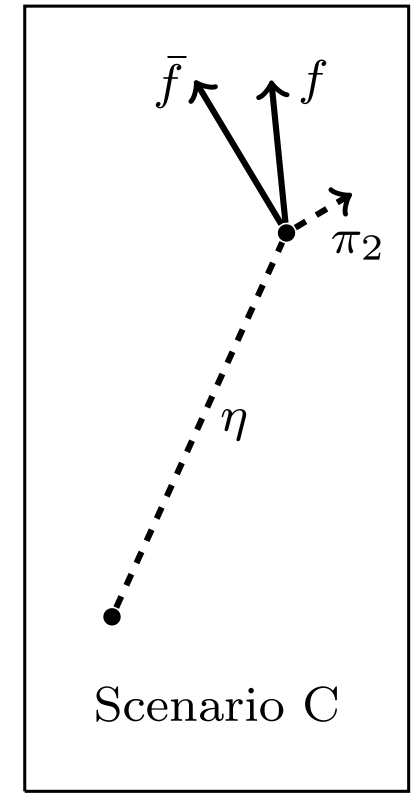


Resonant dimuons
do not point to beamline

A’ off-shell
η long-lived & 3 body



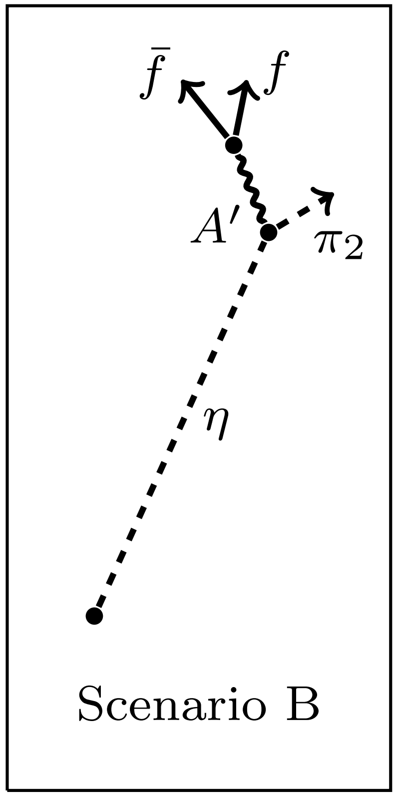
Non-resonant dimuons
do not point to beamline

CMS requires pointing to reduce background from fake displaced vertices

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

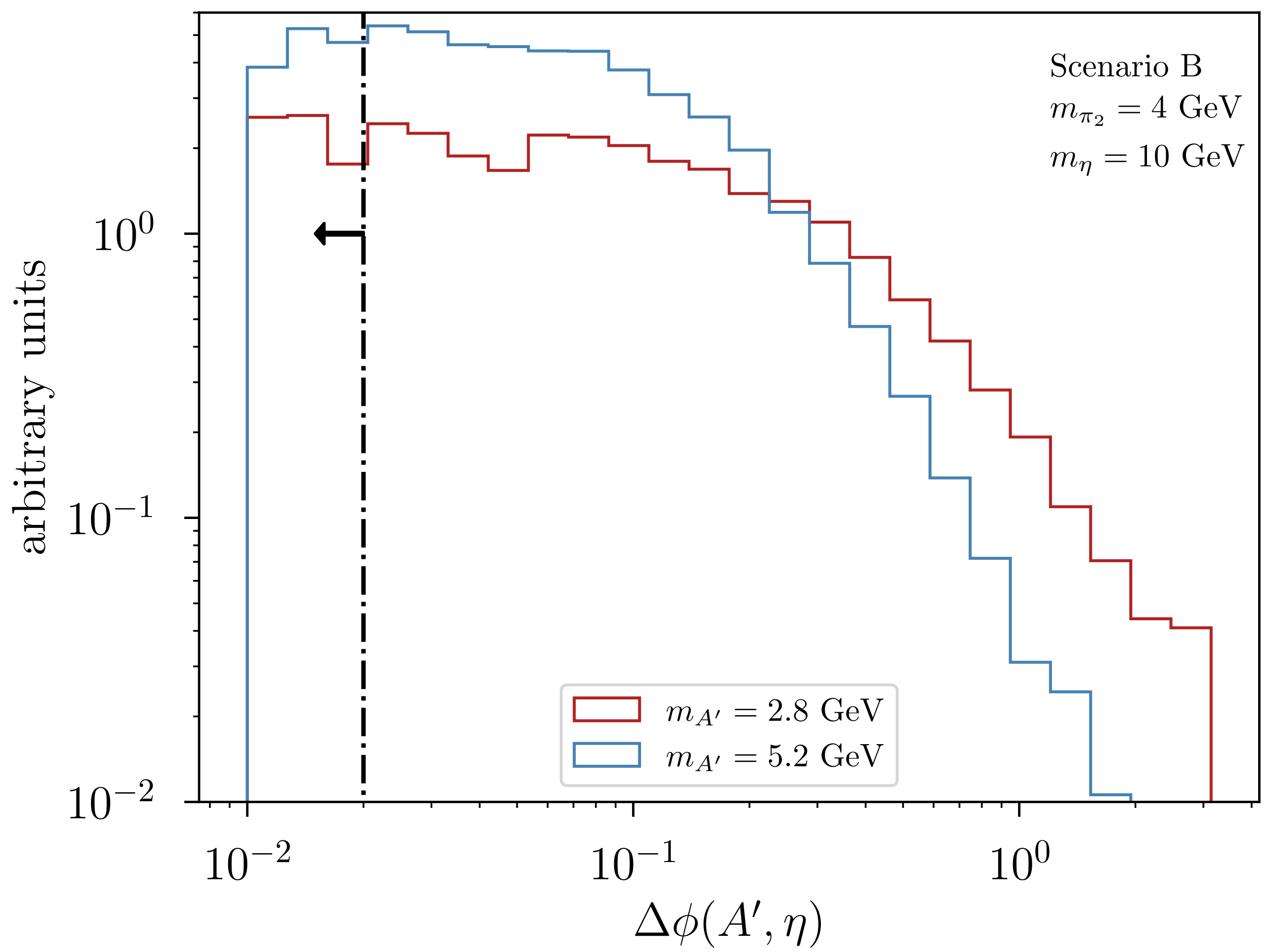
Extending the scouting analysis

A’ decays prompt
η long-lived



Resonant dimuons
do not point to beamline

LHCb search has non-pointing selection, which has more background
CMS signal acceptance is very low

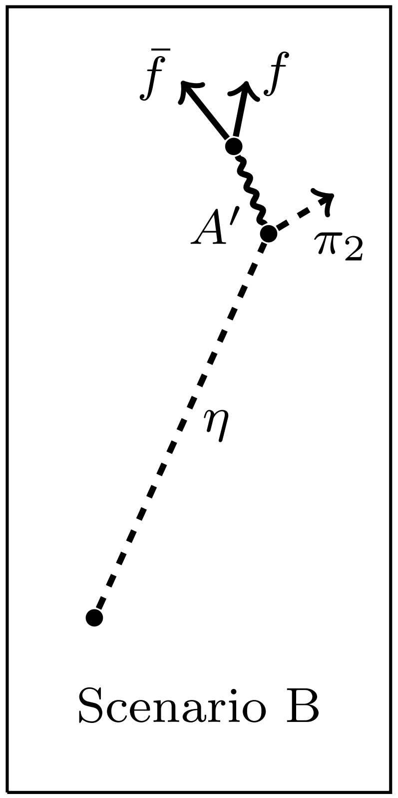


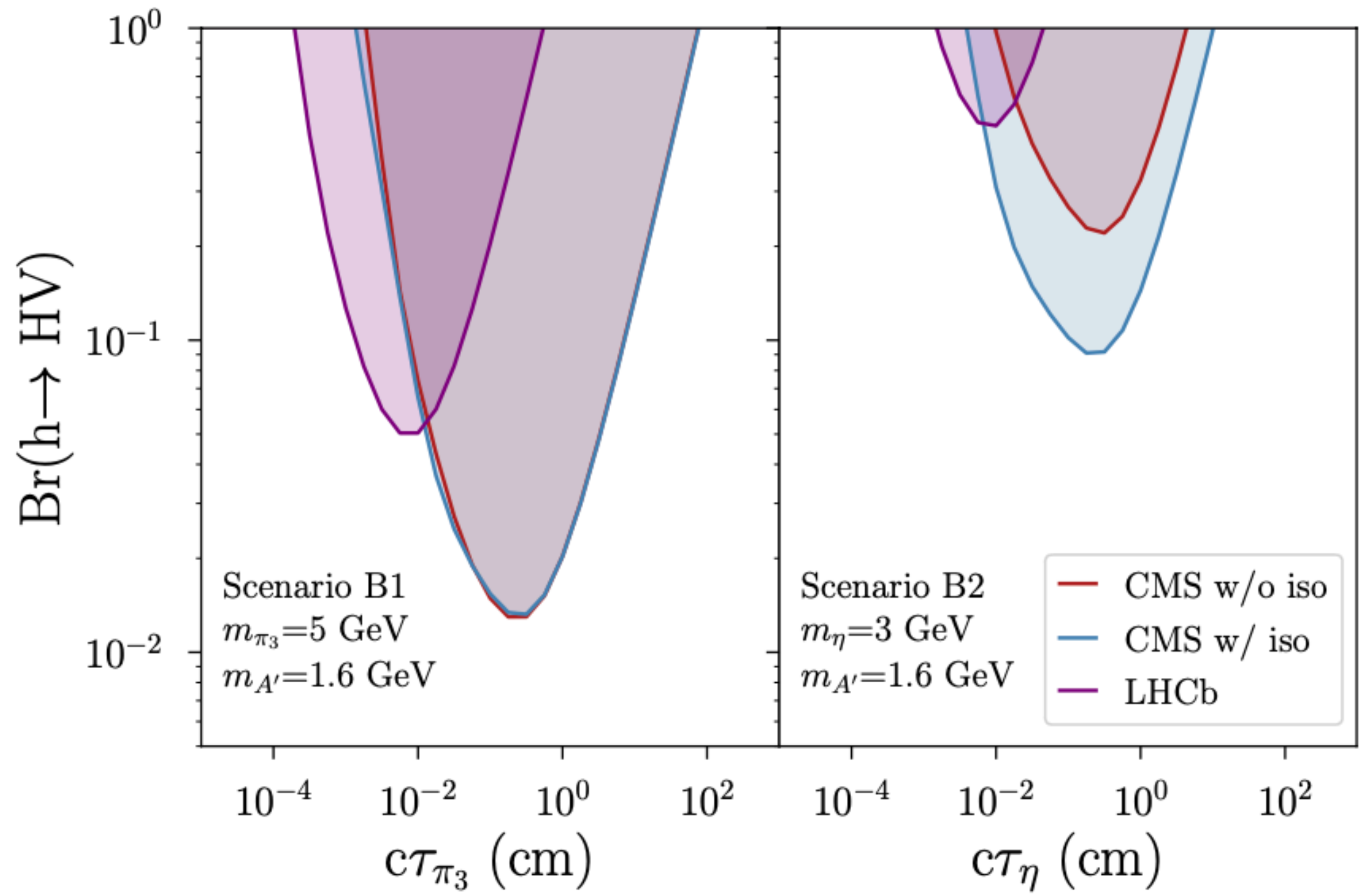
CMS may have sensitivity by considering a non-pointing signal region

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

Scenario B

A' decays prompt
η long-lived





Resonant dimuons
do not point to beamline

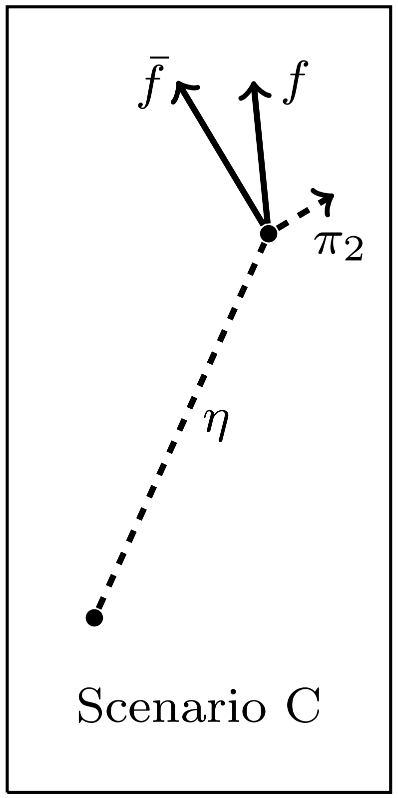
LHCb is currently barely competitive with Higgs global fits

CMS is more competitive and may have better sensitivity by considering a non-pointing signal region

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167

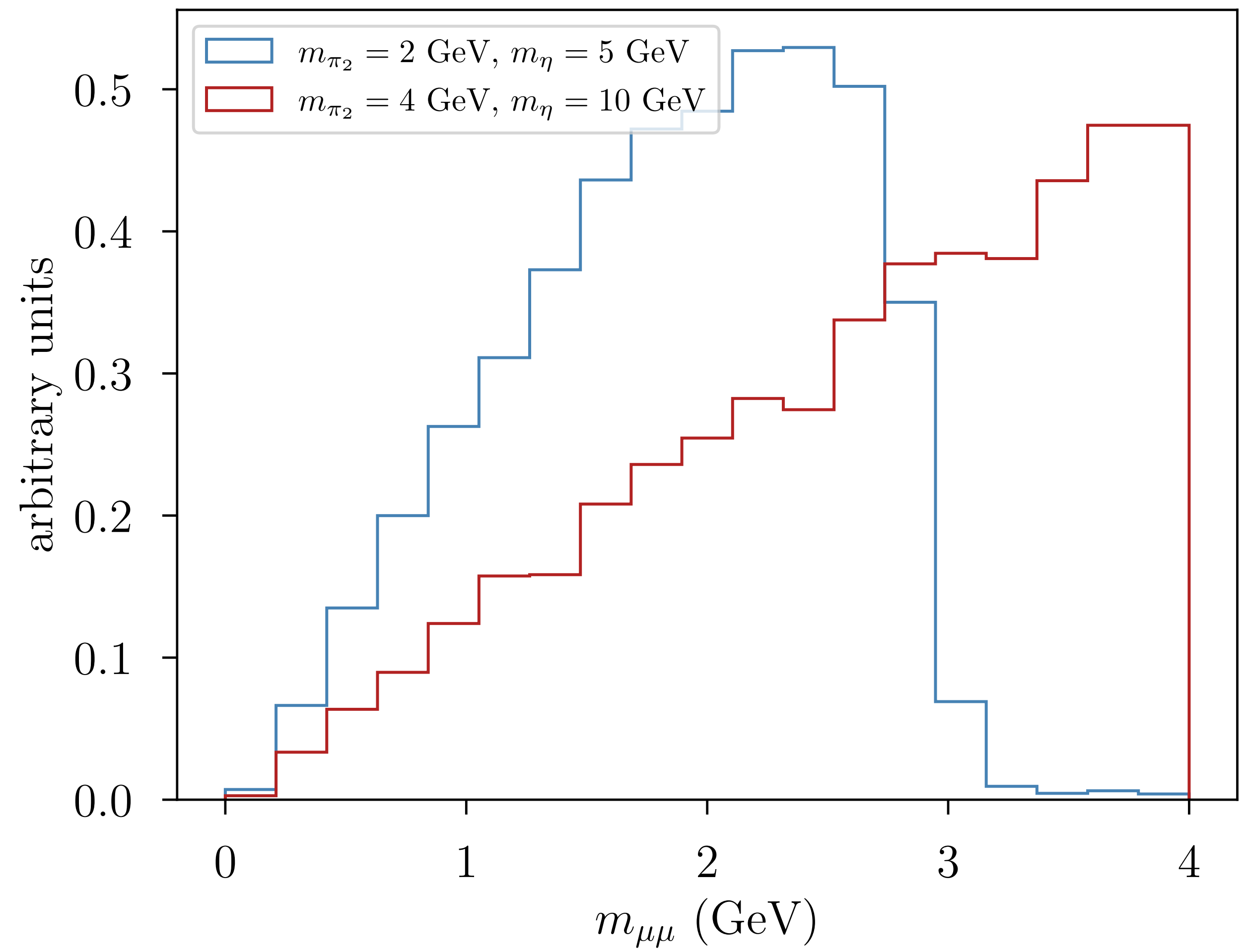
Scenario C

A' off-shell
η long-lived & 3 body



Non-resonant dimuons
do not point to beamline

Neither CMS nor LHCb searches apply atm



CMS may have sensitivity by searching for an end point
(likely very challenging)

Heavy Neutral Leptons (HNL's) produce the same decay topology

S. Born, SK, J. Shelton, R. Karur: arXiv 2303.04167