SCOUTING FOR LIGHT DARK SHOWERS AT THE LHC

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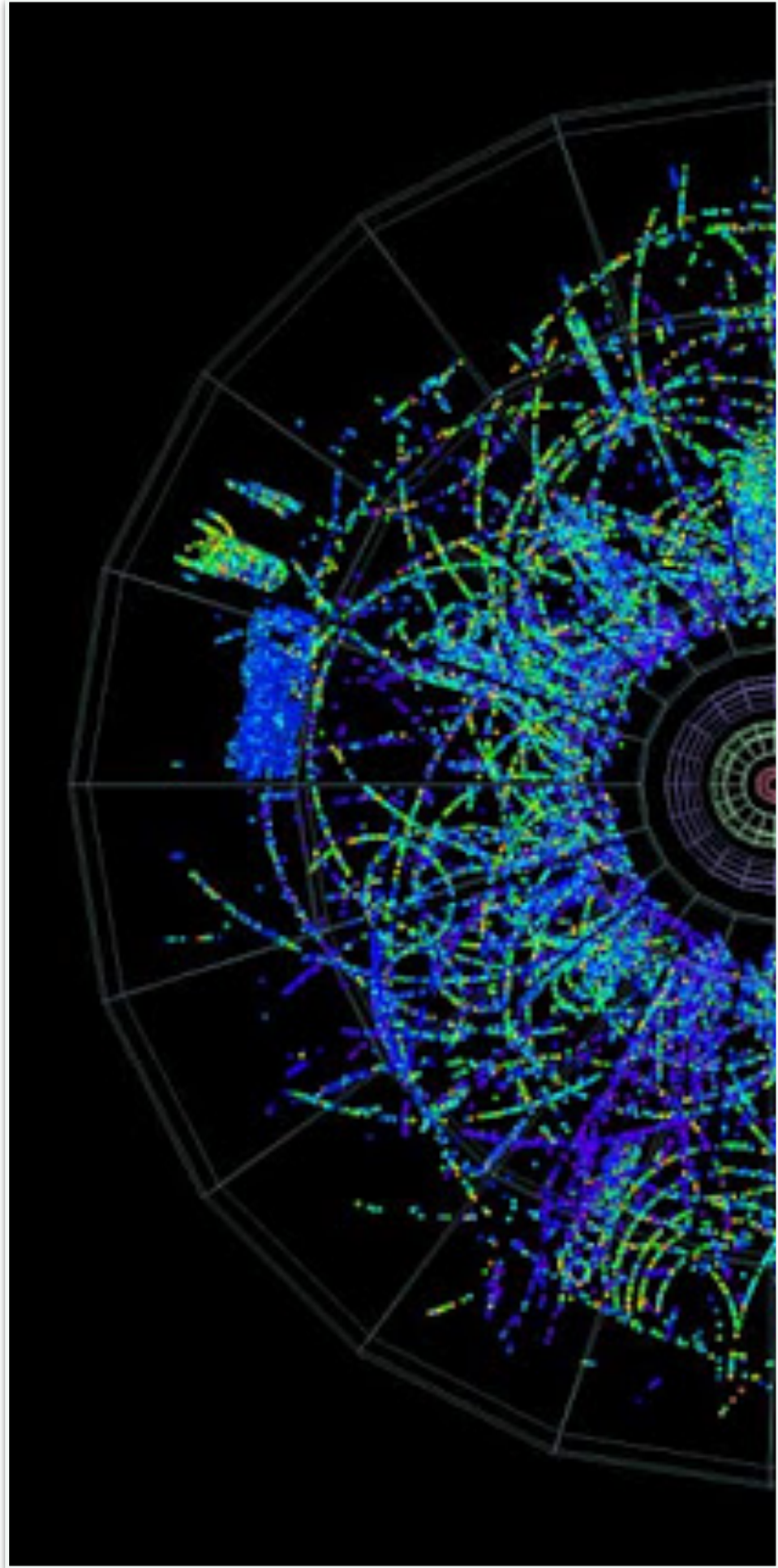
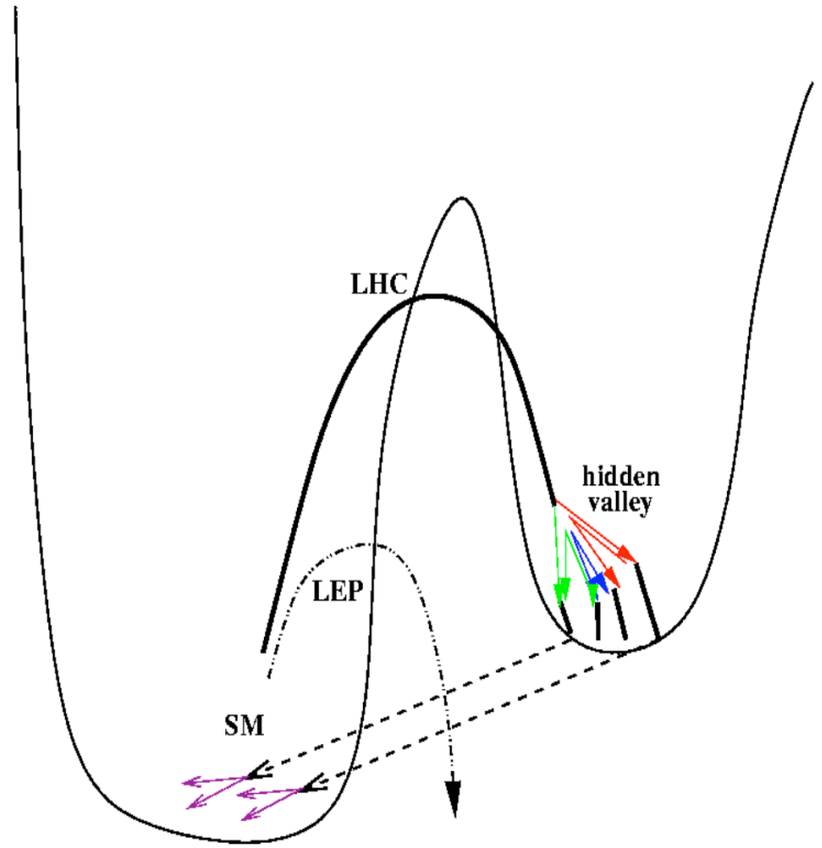
November 22, 2023



CONFINING HIDDEN SECTORS

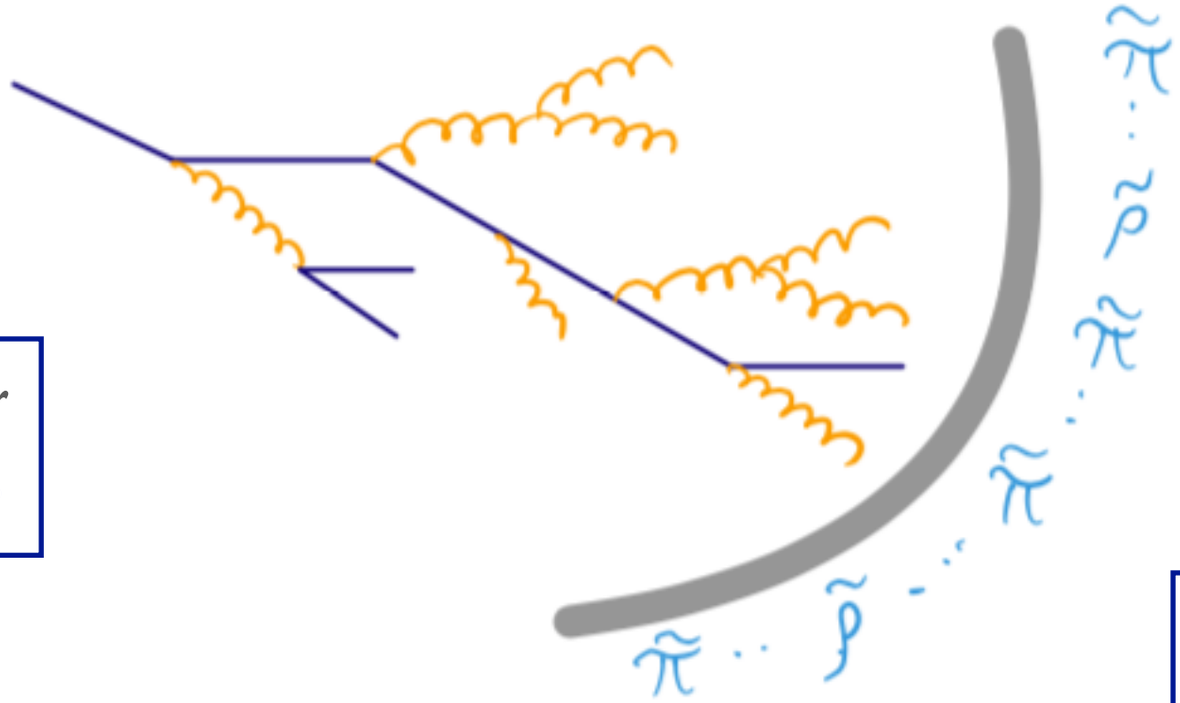
- scenarios where new physics has strong self-interactions: "hidden valleys"
- theoretical motivations:
  - problems of the SM
    - hierarchy problem
    - baryogenesis
    - dark matter
- generic possibility for new physics



[Strassler]

CONFINING HIDDEN SECTORS

- Experimental motivations: confining theories generally predict qualitatively distinct signatures relative to perturbative BSM models: dark showers



parton shower - perturbative

hadronization - nonperturbative

- emerging frontier for current, future LHC runs

DARK SHOWERS

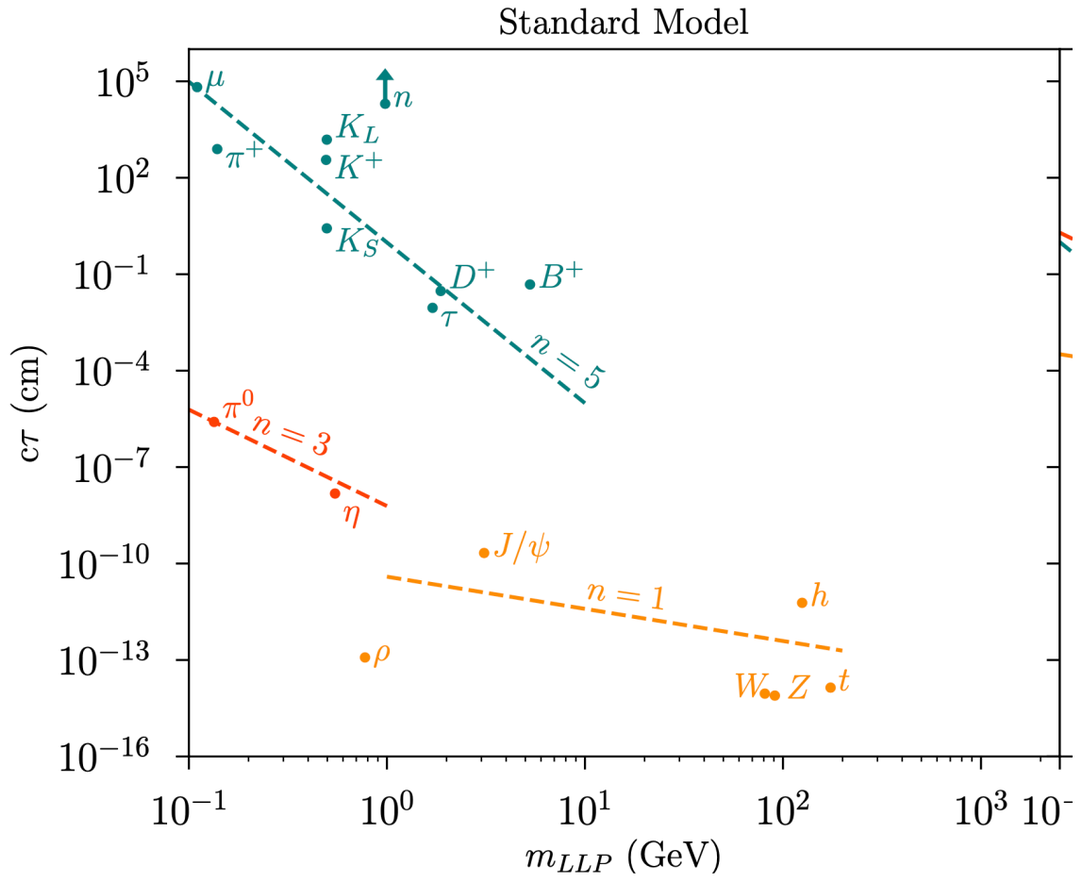
- Dark showers: characteristic features
  - variable and potentially large object multiplicity
  - non-SM-like distributions of energy, flavor
  - often non-isolated final state objects
  - hierarchy of lifetimes

CHALLENGES OF DARK SHOWER SEARCHES

- Experimentally, often hard:
  - may involve novel reconstruction algorithms
  - calibration of background contributions to new observables, new regimes
- Theoretically, hard:
  - enormous and poorly-understood space of theories
  - making predictions in non-perturbative theories is much harder than in perturbative theories
    - in some cases only: low-lying hadron spectra from lattice
    - Monte Carlo tools for hadronization developed for and tuned to QCD

LONG-LIVED PARTICLES

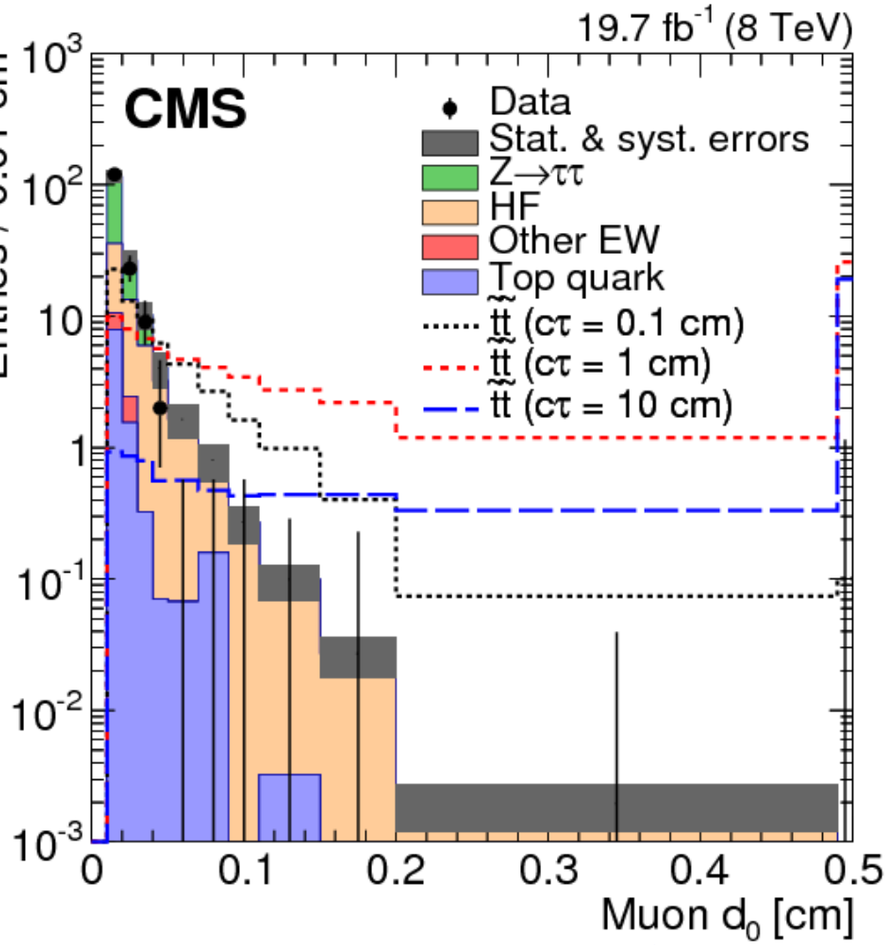
- Confining hidden sectors generically lead to LLPs
  - Composite states decay through high mass dimension operators
  - Accidental global symmetries:
    - discrete, e.g., *CP*
    - (approximate) flavor symmetries, e.g. SM pions
- (Mass-scale dependent) combination of prompt + displaced + detector stable

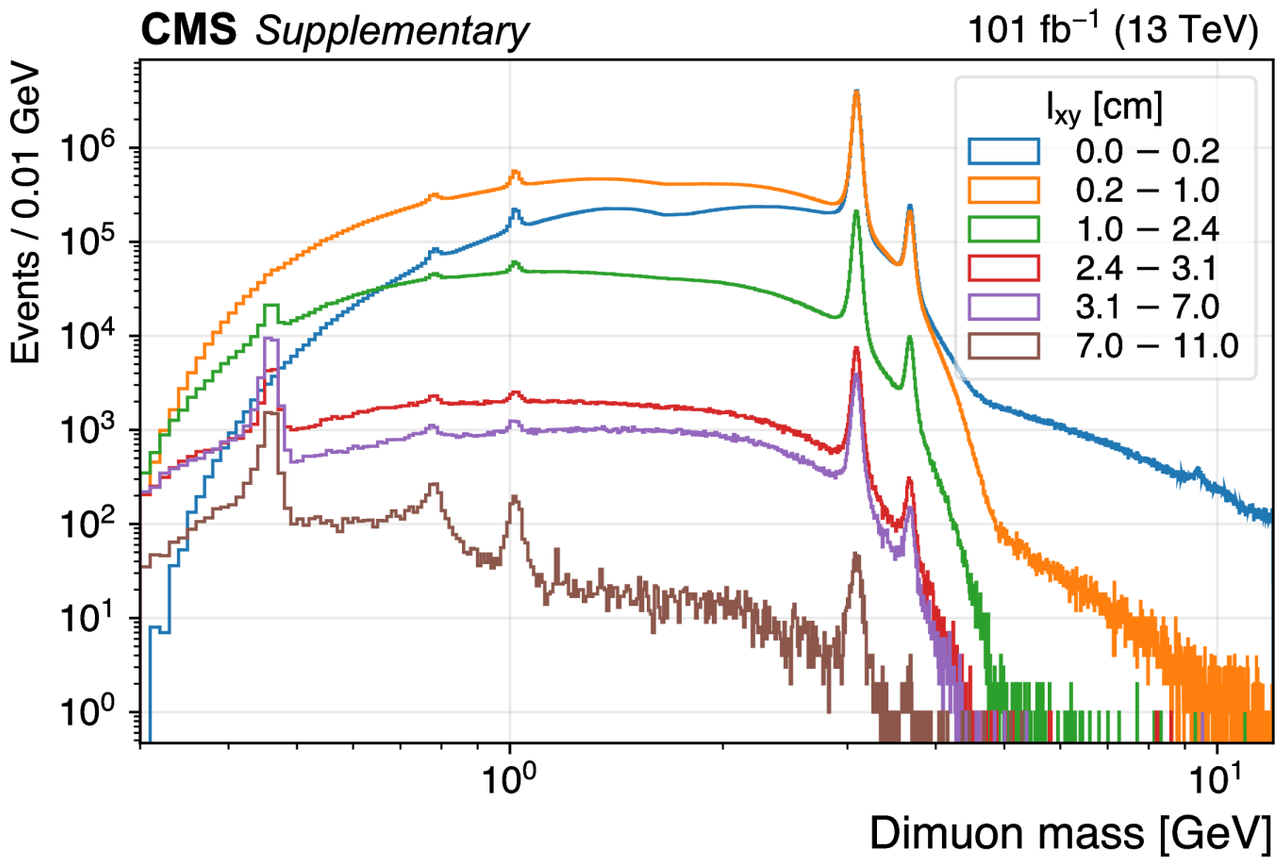


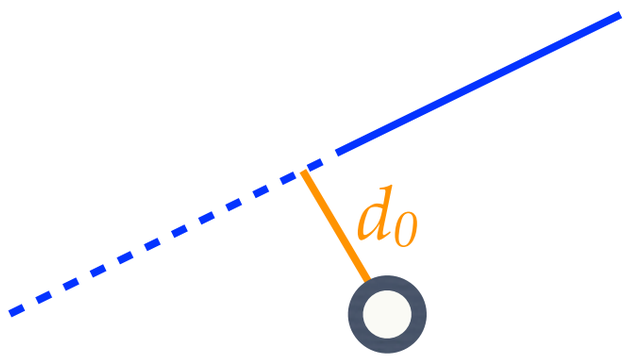
[Knapen, Lowette]

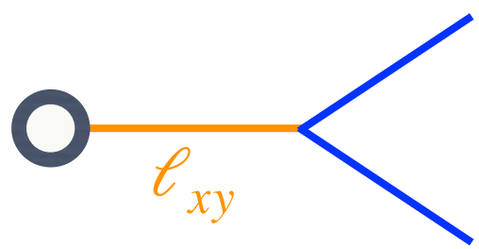
LONG-LIVED PARTICLES

- LLPs can be a powerful tool for suppressing SM backgrounds



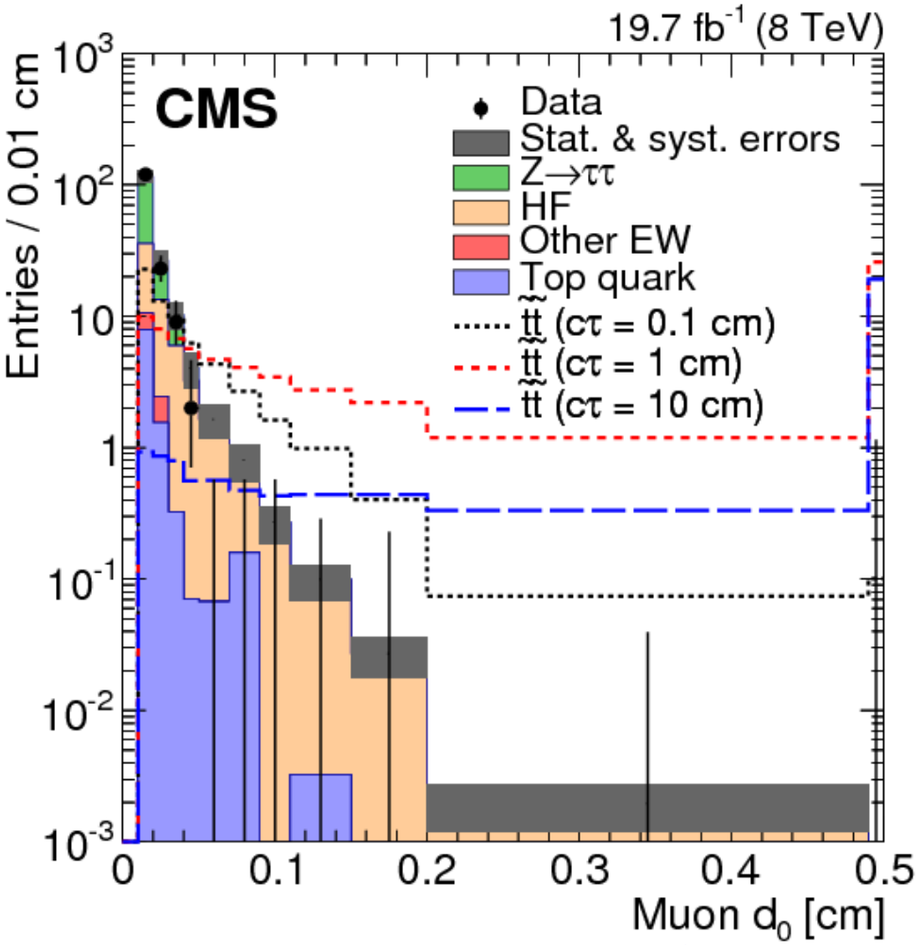


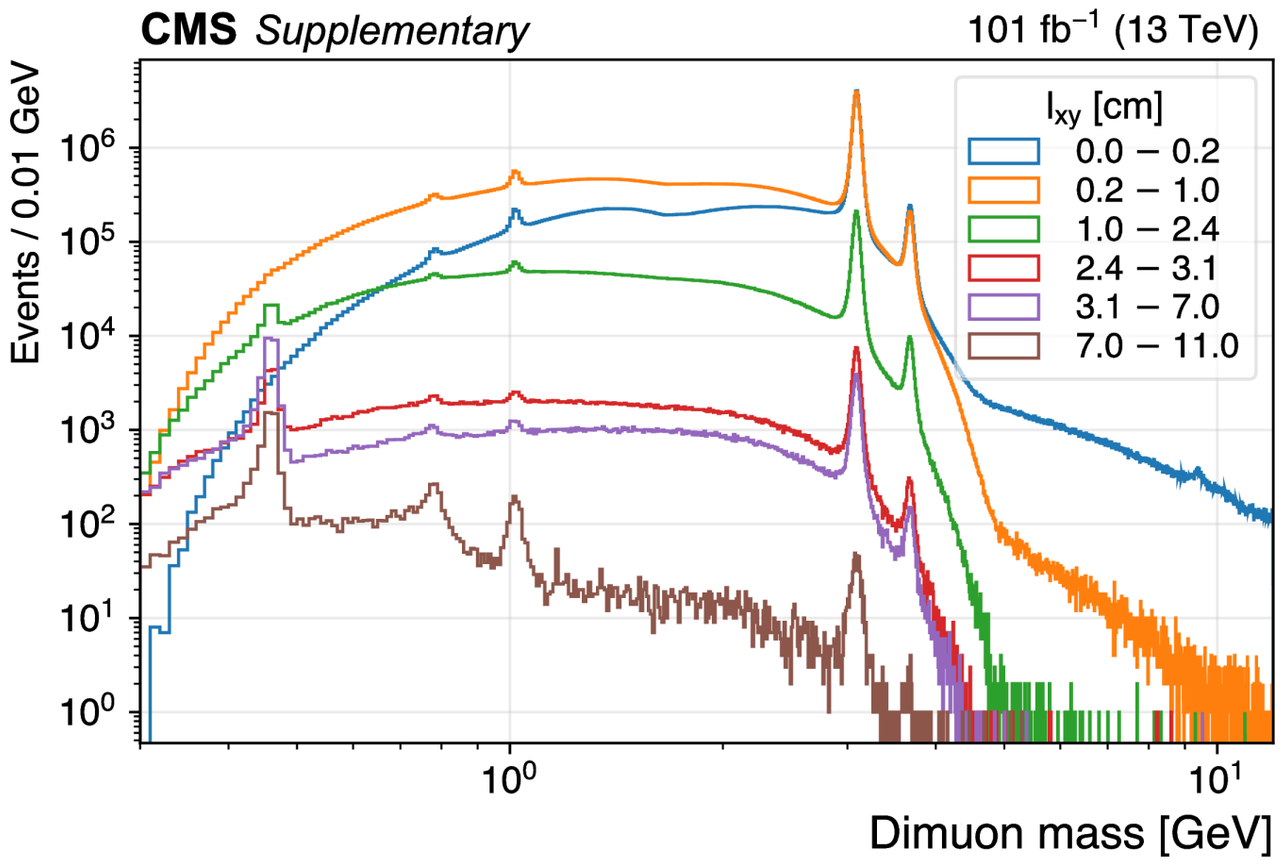


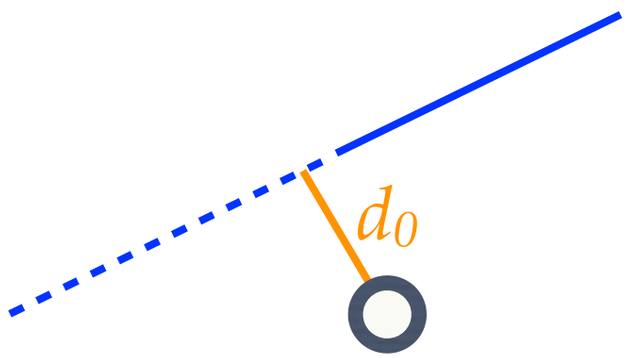


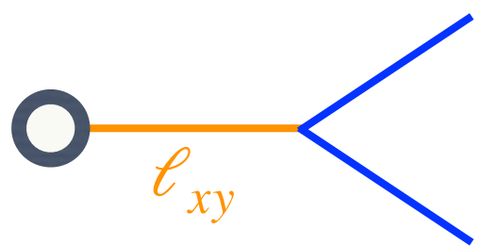
LONG-LIVED PARTICLES

- Displaced searches often relatively insensitive to event details









LONG-LIVED PARTICLES

- Thus LLPs have the potential to offer powerful, relatively inclusive searches
- Especially important in searching for low-mass dark sectors where kinematics is not useful for background rejection
- But:

Detector signal is inextricably tied to multiplicity of specific given dark hadron species

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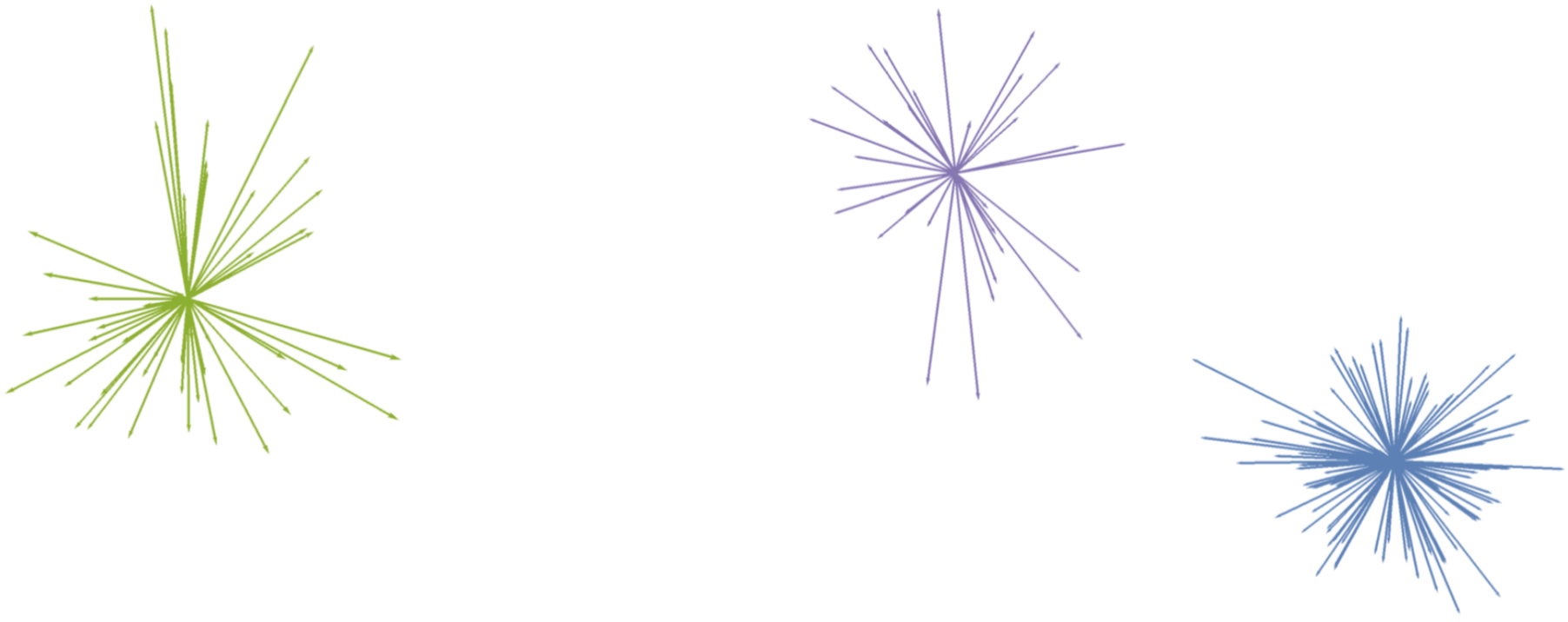
ENERGY DISTRIBUTION

- the existence of jets is also an expectation inherited from QCD
  - at very large 't Hooft coupling $g^2 N_c$ one expects spherical events
  - at moderate 't Hooft coupling…?



[Hoffmann, Maldacena; Strassler; Knapen, Pagan Griso, Papucci, Robinson; Cesarotti, Reece, Strassler]

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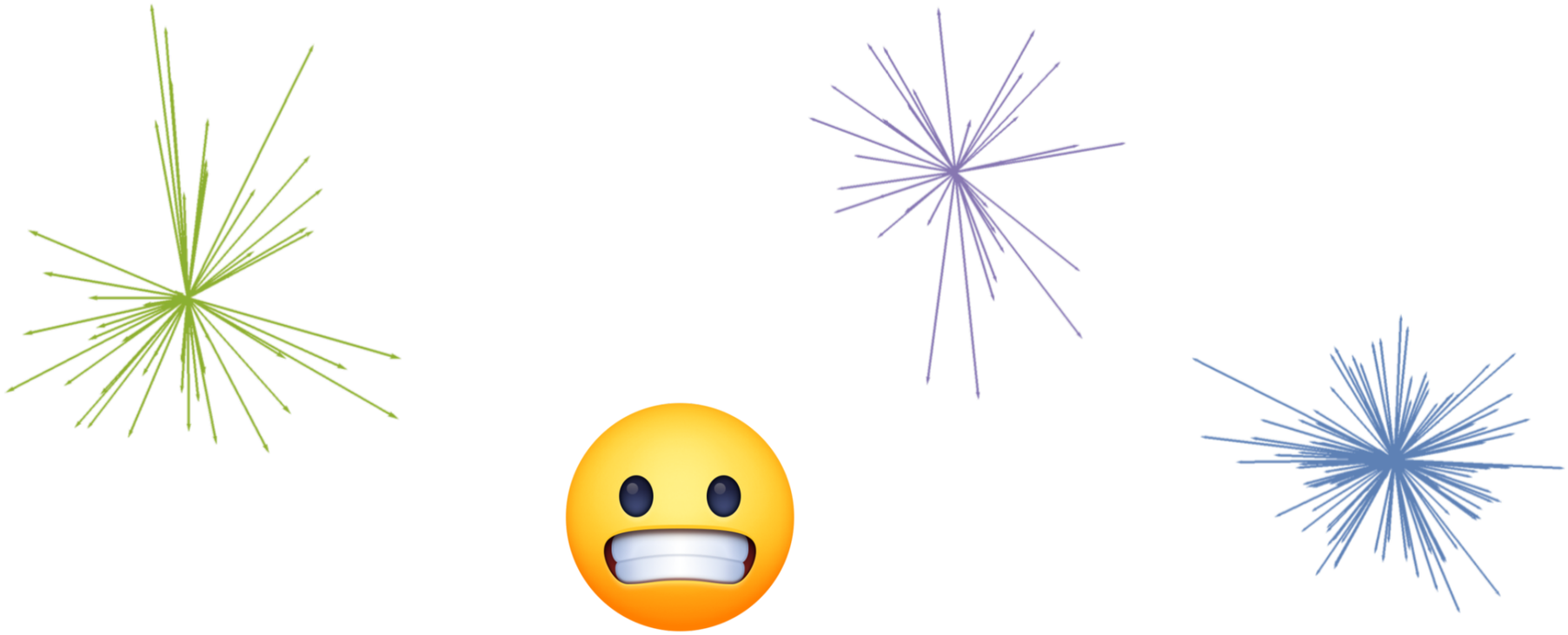
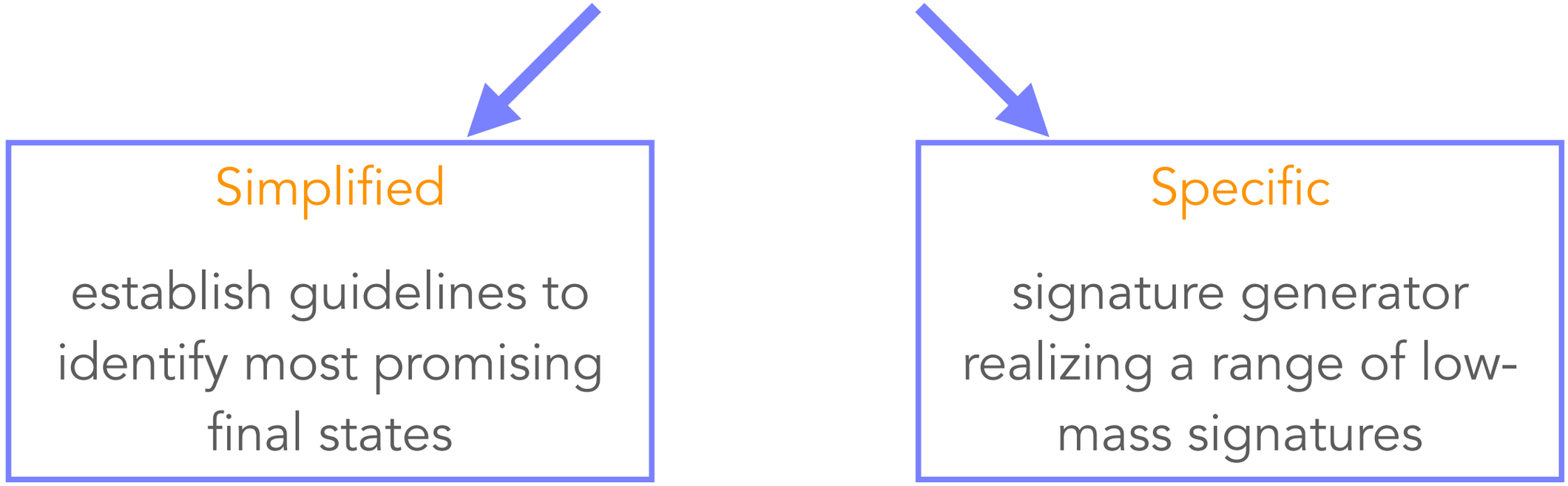


[Hoffmann, Maldacena; Strassler; Knapen, Pagan Griso, Papucci, Robinson; Cesarotti, Reece, Strassler]

INCLUSIVE STRATEGIES FOR DARK SHOWERS

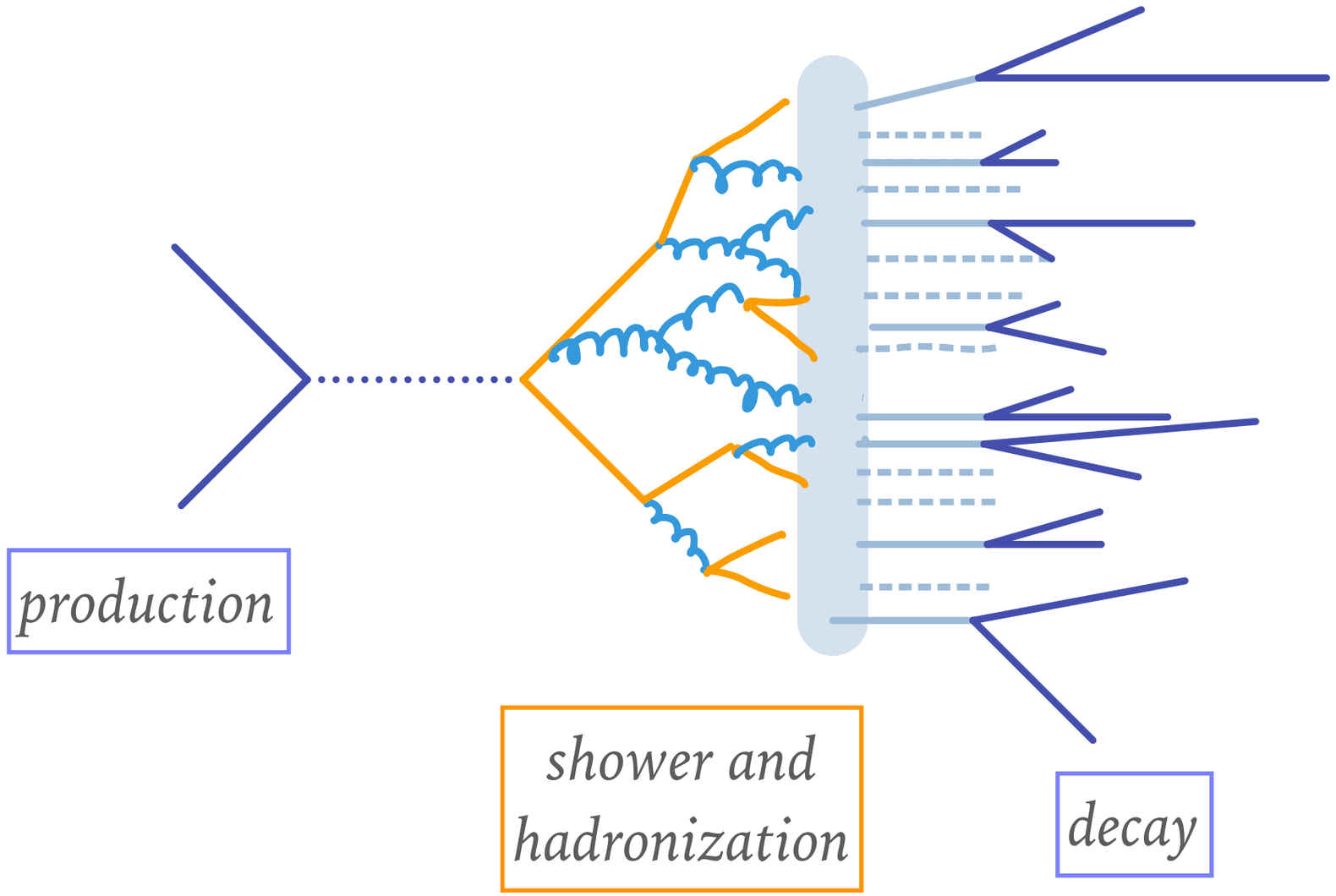
- Develop searches for (multiple) displaced objects at low p_T, prioritize inclusivity at analysis level
- key element in developing broad discovery coverage
- Develop QCD-esque benchmarks for low-mass hidden sectors



[Knapen, JS, Xu; Born, Karur, Knapen, JS]

A DARK SHOWER EVENT

➤ Components of a dark shower event:



PRODUCTION

- Primary focus: production in exotic decays of SM Higgs boson
  - minimal; well-motivated
  - low mass:
    - challenging benchmark for trigger, analysis development
      - sensitivity to soft LLPs helps mitigate uncertainties about multiplicities, event shape
  - built-in triggering fall-back through *VH* associated production
- (Alternative: *s*-channel production through BSM mediator related to decay portal)

[Knapen, JS, Xu]

EVOLUTION

- Use Pythia 8 Hidden Valley module
  - SU(N_c) with N_f flavors: most reliable for SM N_c=3
  - QCD-like parton shower evolution
  - QCD-informed hadronization model

- stripped-down hadron sector: spin-1, spin-0 mesons only
  - dark flavor symmetries newly breakable: v3.807+
- adjusting the meson mass hierarchy, production probabilities controls visible multiplicity
- this is a simplified model; its predictions must be considered part of the model definition

[Carloni, Sjostrand; Carloni, Rathsman, Sjostrand; Strassler, Sjostrand +]

DECAY

- Choice of decay portal governs detector signatures:

Decay portal	decay operator	features
gluon portal	$\tilde{\eta} G^{\mu\nu} \tilde{G}_{\mu\nu}$	hadron rich
photon portal	$\tilde{\eta} F^{\mu\nu} \tilde{F}_{\mu\nu}$	photon shower
vector portal	$\tilde{\omega}^{\mu\nu} F_{\mu\nu}$	semi-visible jet
Higgs portal	$\phi H^\dagger H$	heavy flavor rich
dark photon portal	$\tilde{\eta} F'^{\mu\nu} \tilde{F}'_{\mu\nu} + \epsilon F'^{\mu\nu} F_{\mu\nu}$	hadrons + leptons

- guiding philosophy:
  - operator dimension up to 5
  - no BSM flavor violation
  - plus one model in close analogy to SM pion decay
- span wide range of phenomenological signatures

[Knapen, JS, Xu]

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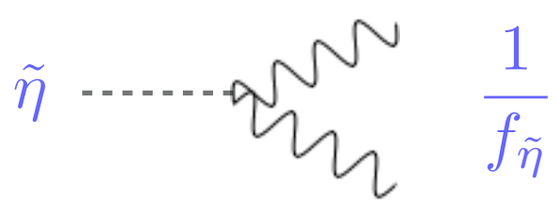
LIGHT DARK HADRON DECAY

- Light dark mesons are generically long-lived*
  - direct bounds on portal couplings
  - composite operators
  - model-building for heavy states in UV completion



- Gluon portal example:

[Knapen, JS, Xu]

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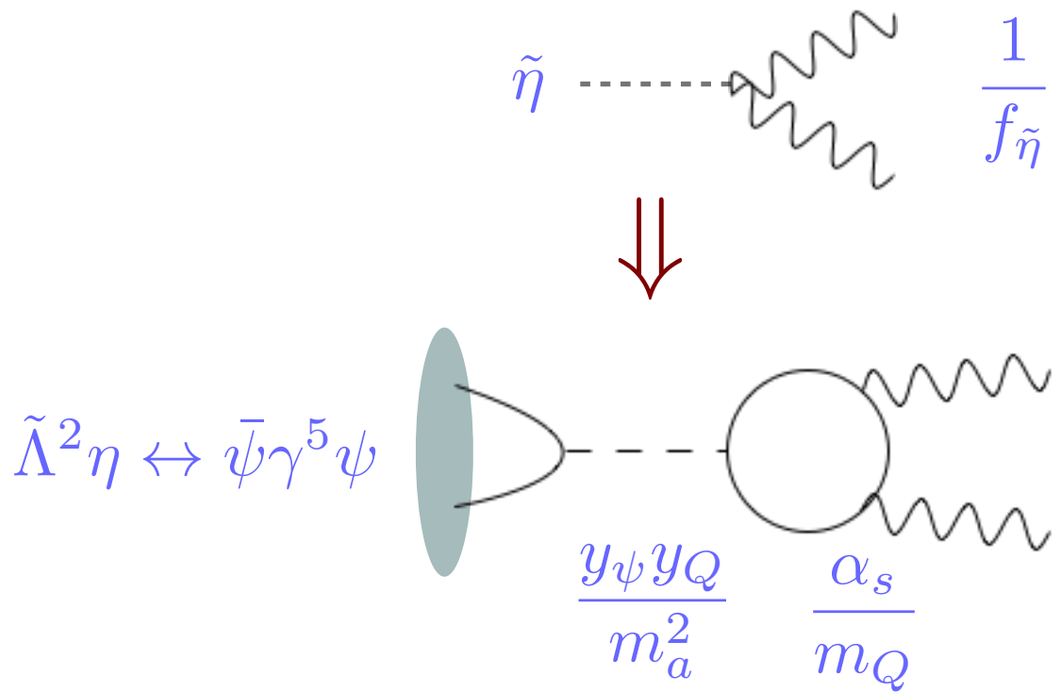

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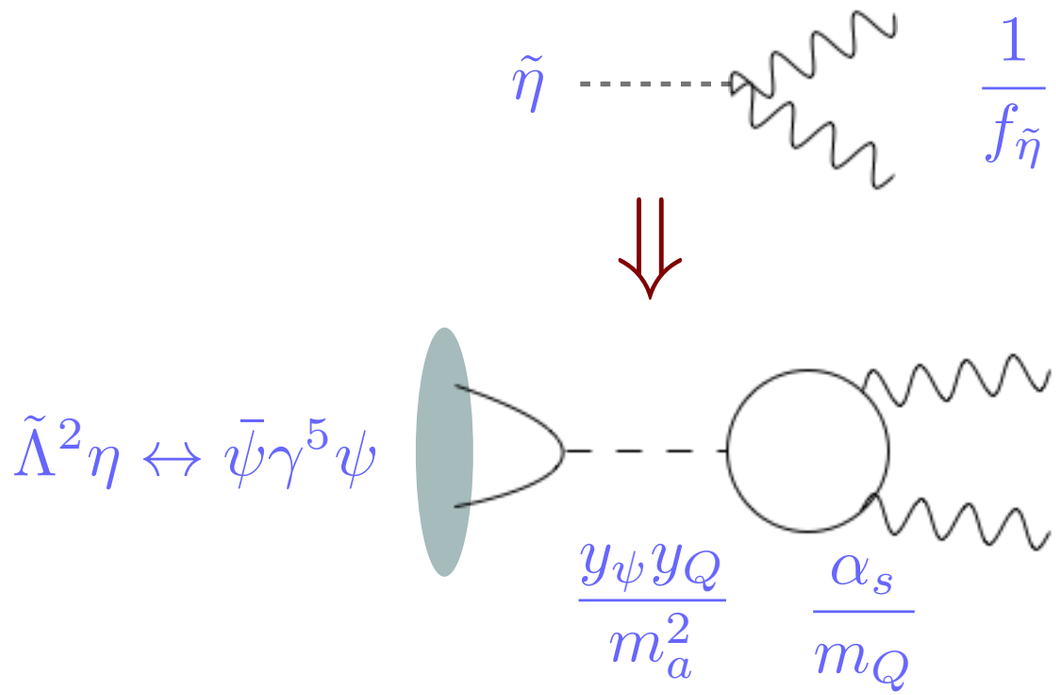


- Gluon portal example:

$$\frac{1}{f_{\tilde{\eta}}} = \frac{y_Q y_\psi N_Q \tilde{\Lambda}^2}{m_a^2 m_Q}$$

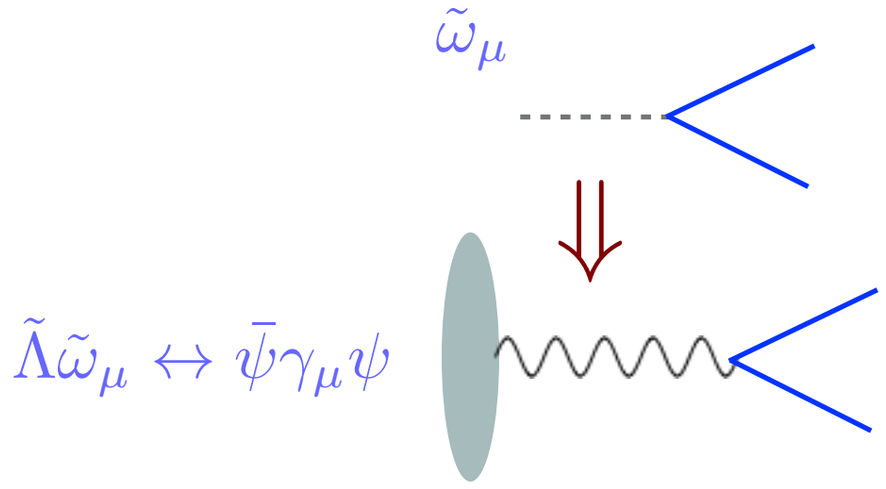
- estimate minimum feasible lifetime:
  - m_Q = 2 TeV; y = 3, N_Q=1

$$c\tau \gtrsim 7\,\mathrm{cm} \times \left(\frac{m_a}{500\,\mathrm{GeV}}\right)^4 \times \left(\frac{5\ \mathrm{GeV}}{m_{\tilde{\eta}}}\right)^7 .$$

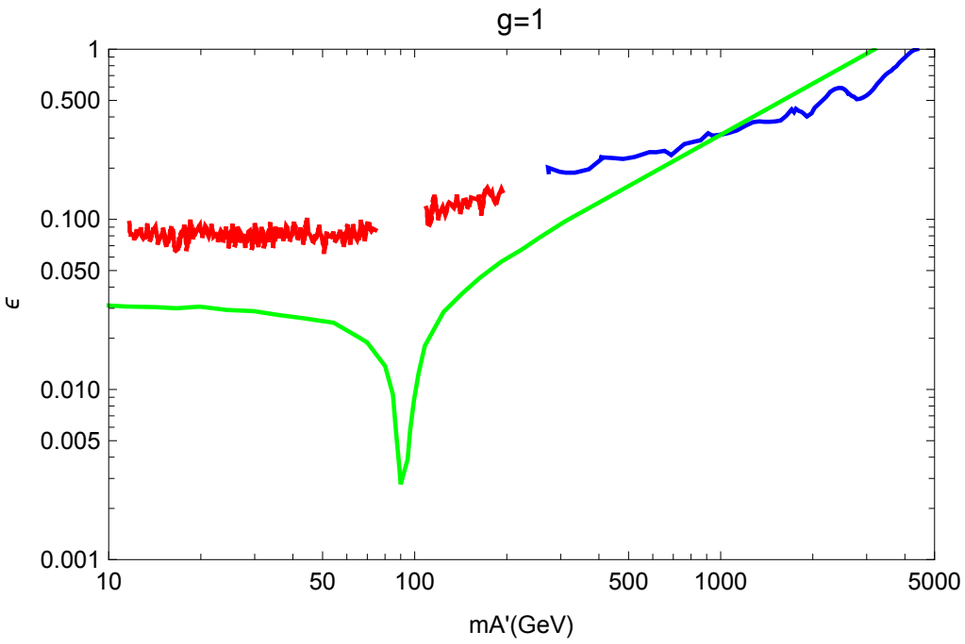
[Knapen, JS, Xu]

LIGHT DARK HADRON DECAY

- Vector portal example:
  - UV completion requires a kinetically-mixed dark photon: constraints from precision electroweak



$$\epsilon_{\text{eff}} \approx g\frac{m_\omega^2}{m_{A'}^2}\epsilon$$

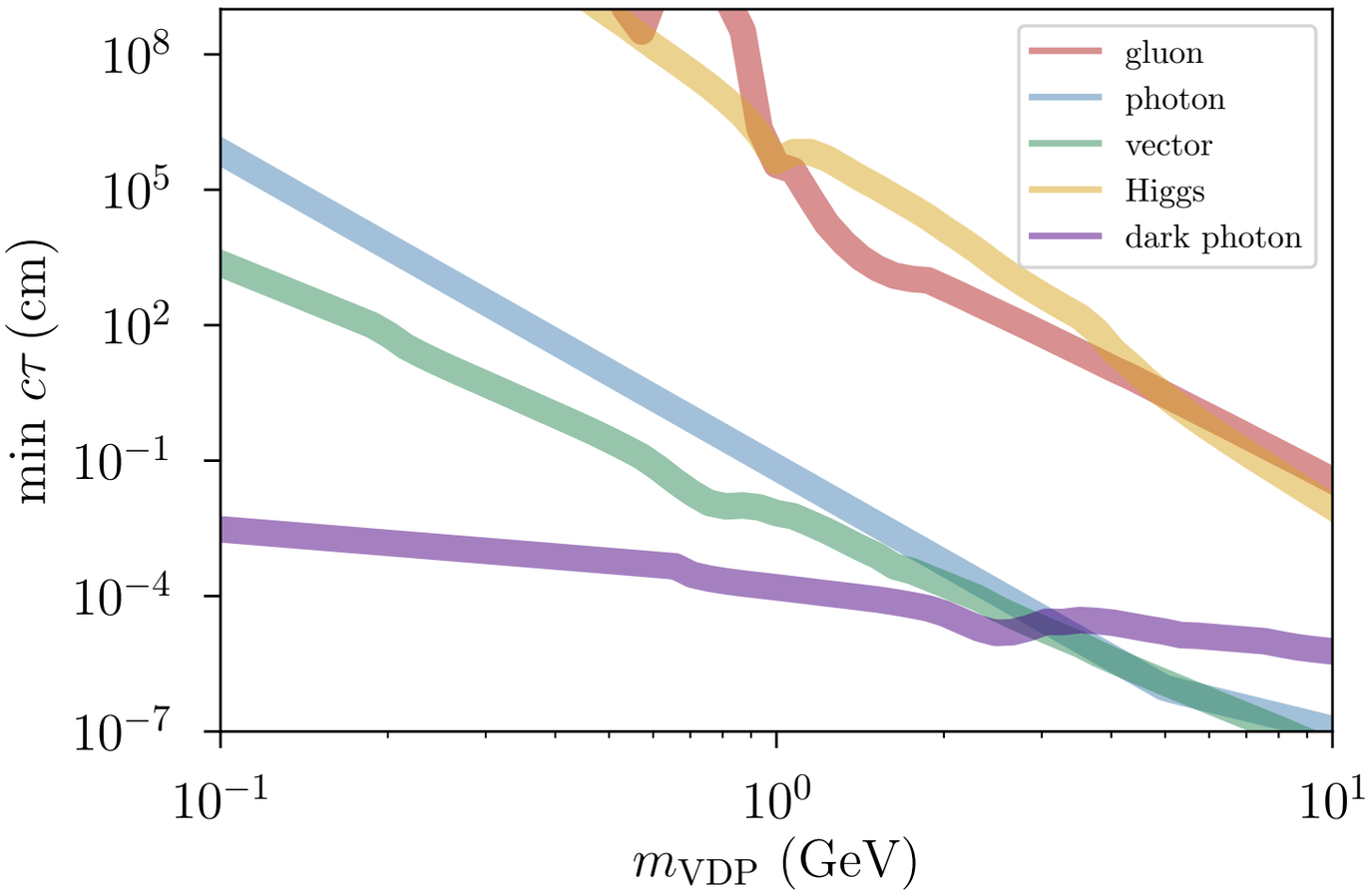


$$c\tau \gtrsim 4\times 10^{-2}\,\text{cm} \times \left(\frac{2\,\text{GeV}}{m_{\tilde{\omega}}}\right)^5 \times \left(\frac{m_{A'}}{20\ \text{GeV}}\right)^4 \times \left(\frac{10^{-2}}{\epsilon}\right)^2$$

[Knapen, JS, Xu]

LIGHT DARK HADRON DECAY

- resulting theoretical estimates for minimum reasonably achievable dark hadron lifetime:



- not hard lower bounds! rather: guides to understand where high multiplicity signatures are most interesting

[Knapen, JS, Xu]

LOW-PT DI-MUONS

- (Displaced) muons at low mass:
  - vector portal interactions enable detector-scale decays for even light BSM species, muon-philic decays
  - Muonic final state well-reconstructable even at trigger level
- Special triggers for low-threshold di-muons:
  - CMS (Data Scouting): partial event reconstruction, retention: muon track, isolation information only
    - $p_{T,\mu} > 3\,\mathrm{GeV}$
  - c.f. LHCb (Turbo Stream): fully online reconstruction, reduced event format

SCOUTING FOR DARK SHOWERS

- A hidden valley model that produces a range of (low-pT, displaced) dimuon signatures

  - $N_c = 3$, $N_f = 2$
  - elementary dark photon with chiral couplings to dark quarks
  - Abelian dark Higgs
  - Yukawa interactions (flavor basis) misaligned with gauge basis

	q_1	q_2	$\bar{q}_1$	$\bar{q}_2$	ϕ
$SU(N_c)$	$\square$	$\square$	$\overline{\square}$	$\overline{\square}$	1
$U(1)$	1	-1	0	0	1

[Born, Karur, Knapen, JS]

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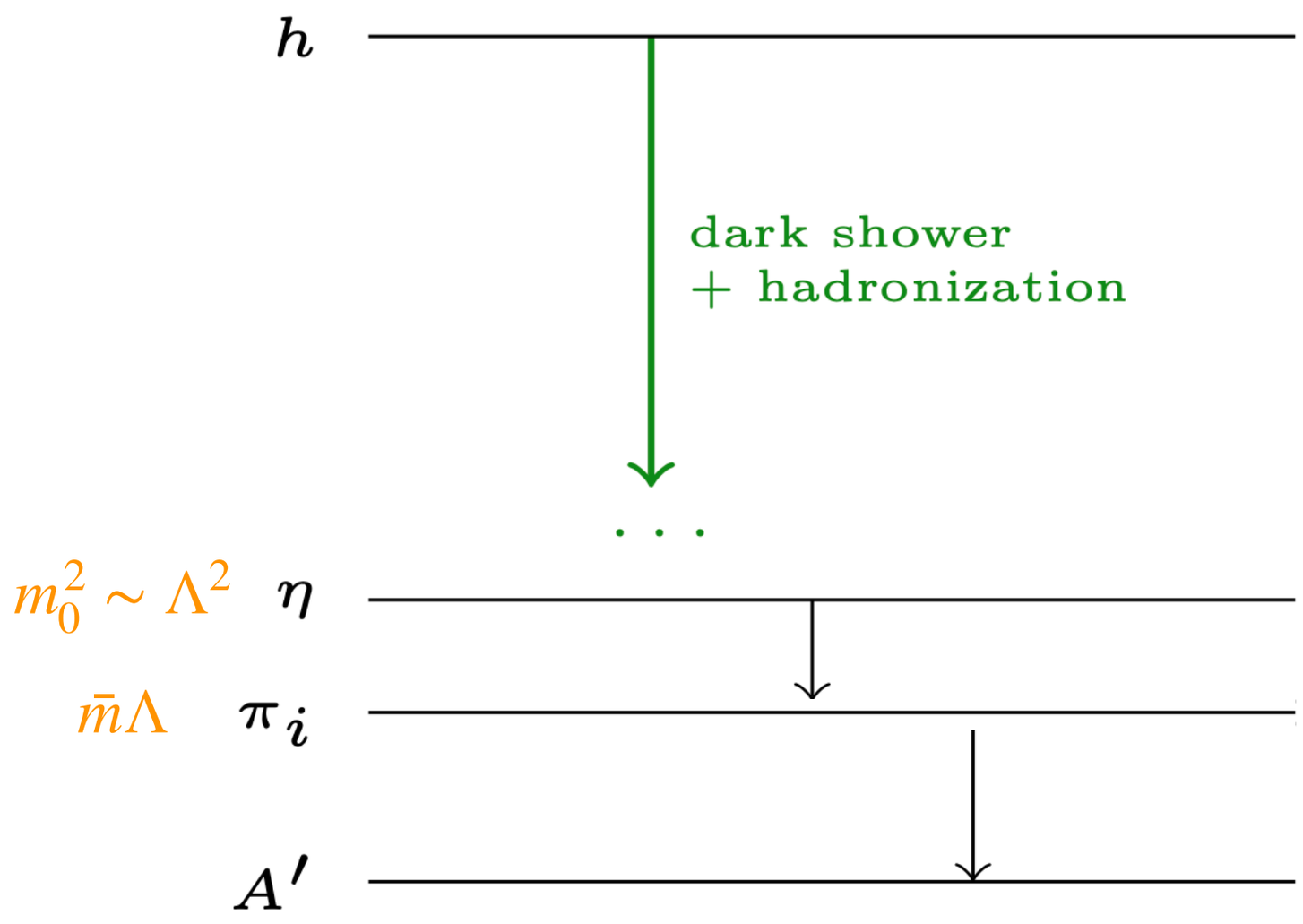
  - Spin-zero mesons: $\tilde{\eta}, \tilde{\pi}_i$
  - massive elementary dark photon
  - Higgs-portal production: exotic Higgs decays

[Born, Karur, Knapen, JS]

MASS SPECTRUM



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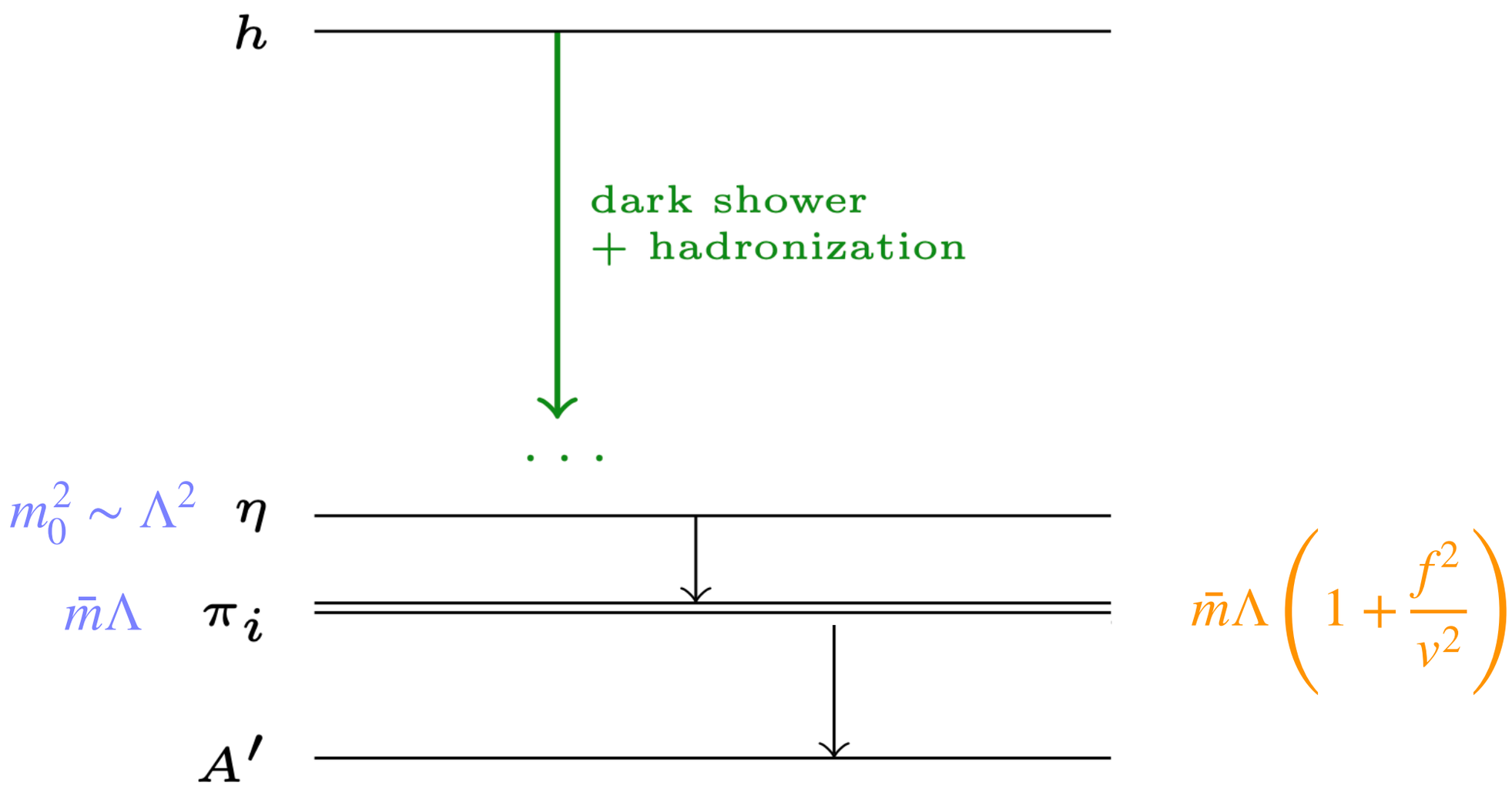

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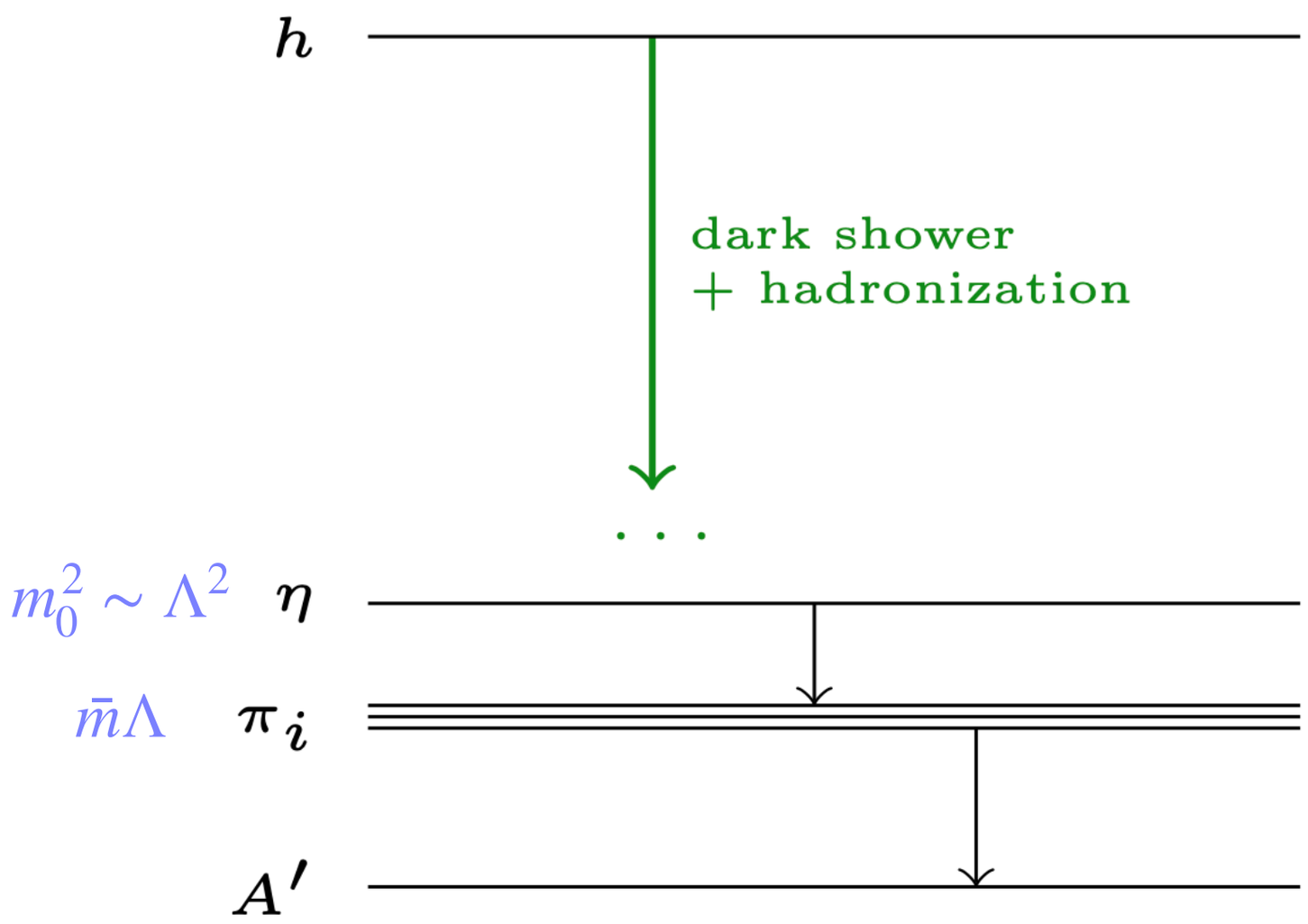


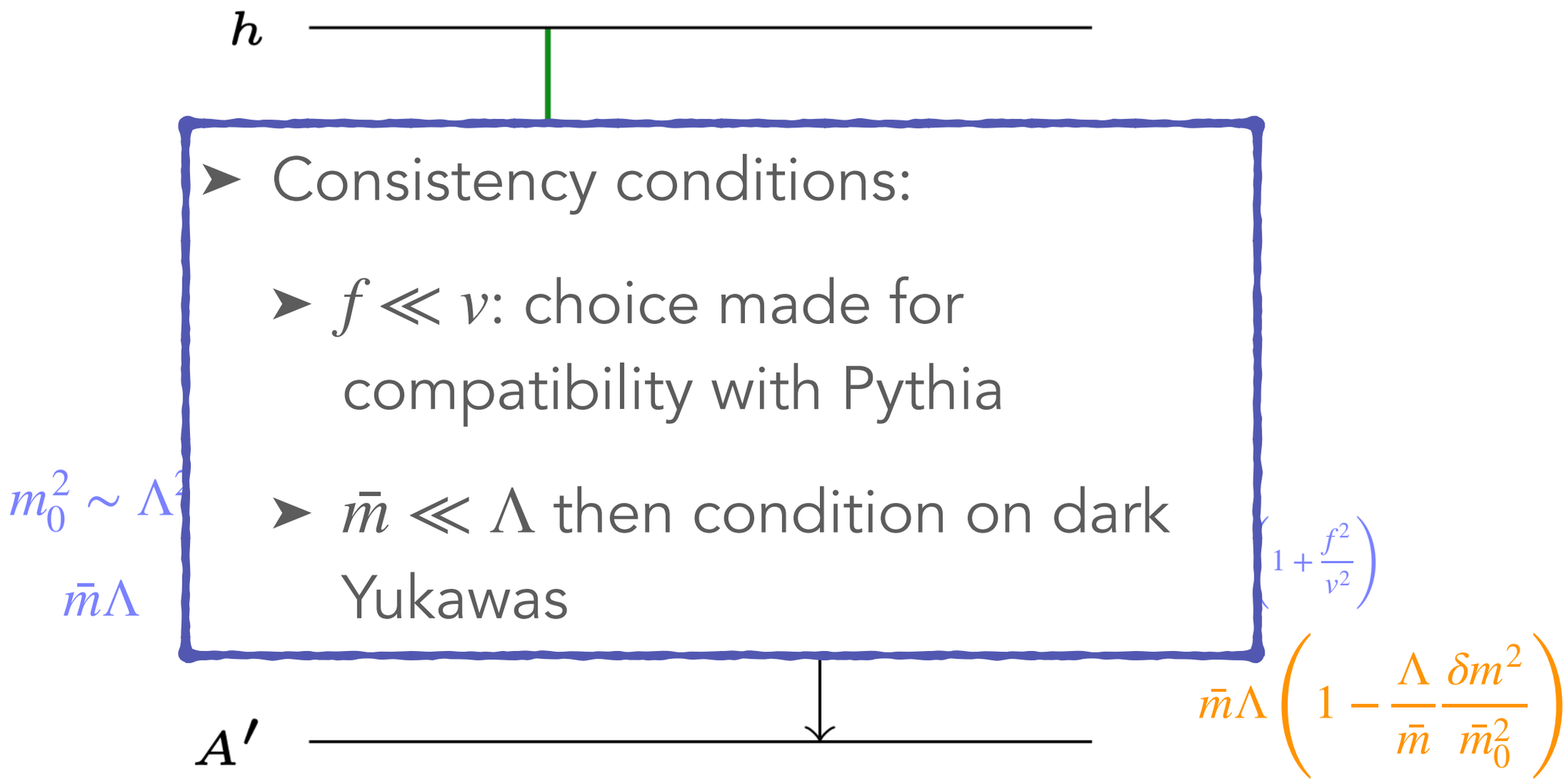
$$\bar{m}\Lambda\left(1+\frac{f^2}{v^2}\right)$$

$$\bar{m}\Lambda\left(1-\frac{\Lambda}{\bar{m}}\frac{\delta m^2}{\bar{m}_0^2}\right)$$

$$m_{A'} = g_D\sqrt{v^2+f^2}$$

[Born, Karur, Knapen, JS]

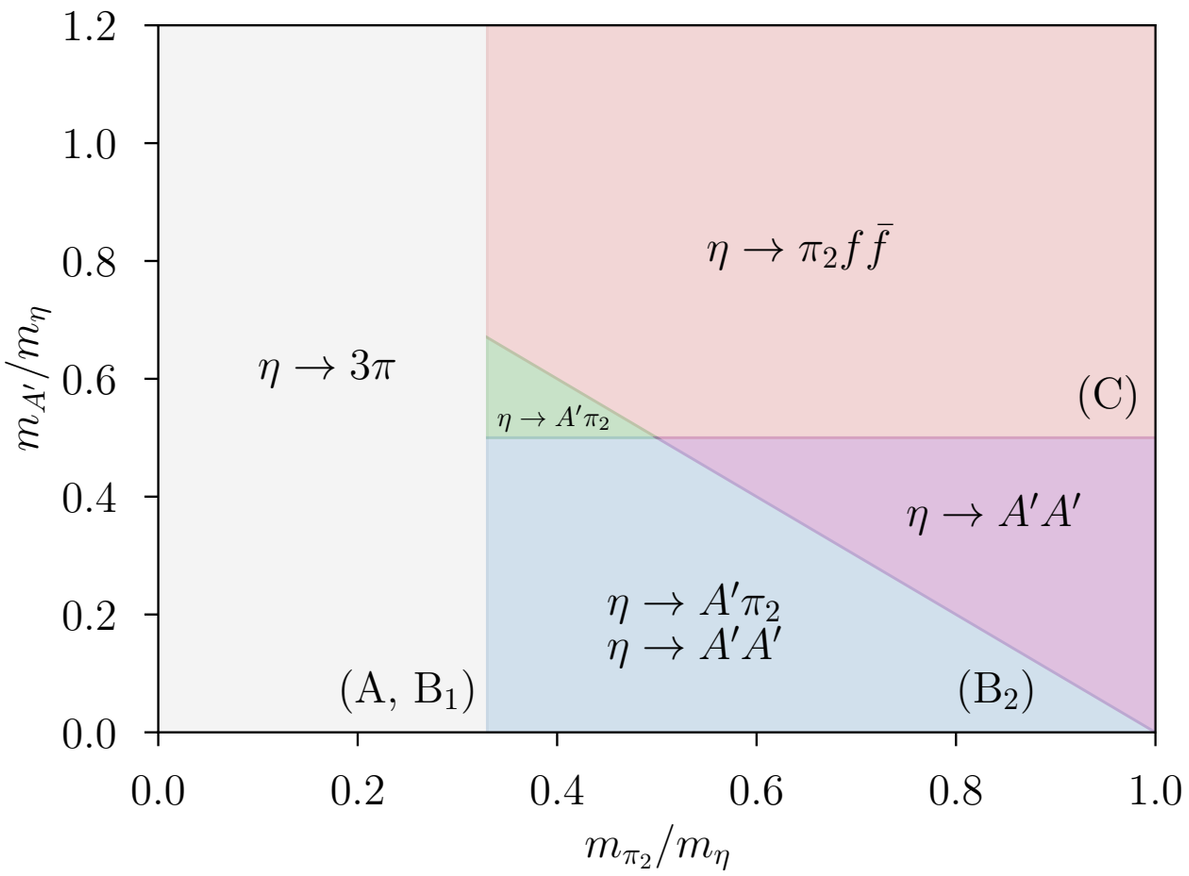
MASS SPECTRUM



[Born, Karur, Knapen, JS]

MESON DECAYS

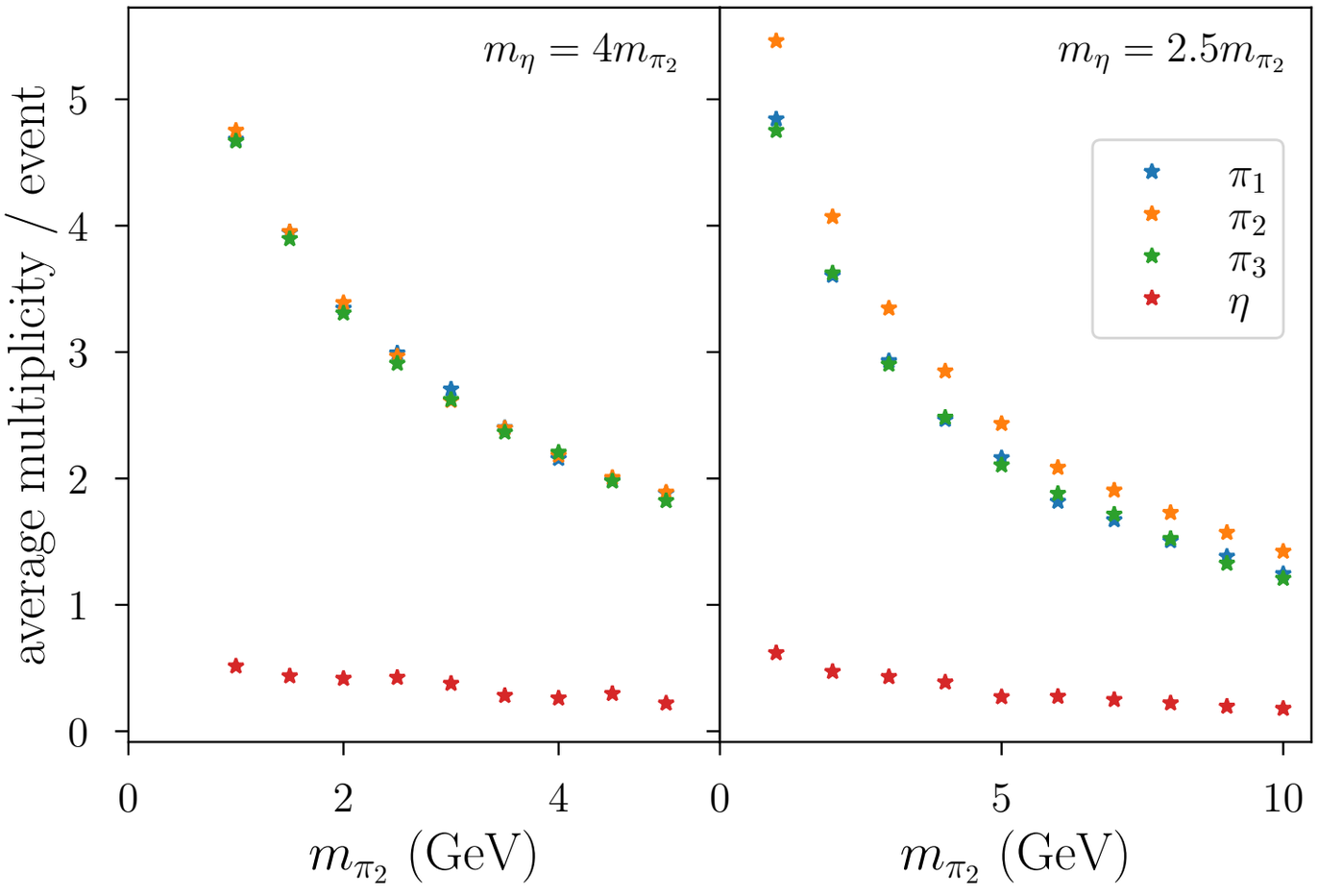
- $\tilde{\pi}_3, \tilde{\eta}$ can decay though dark chiral anomaly: $\tilde{\eta} \to A'A'$
- dark flavor breaking also enables $\tilde{\eta} \to \tilde{\pi}_2 A'$



[Born, Karur, Knapen, JS]

MESON MULTIPLICITY

- Depends on meson mass, mass hierarchy:

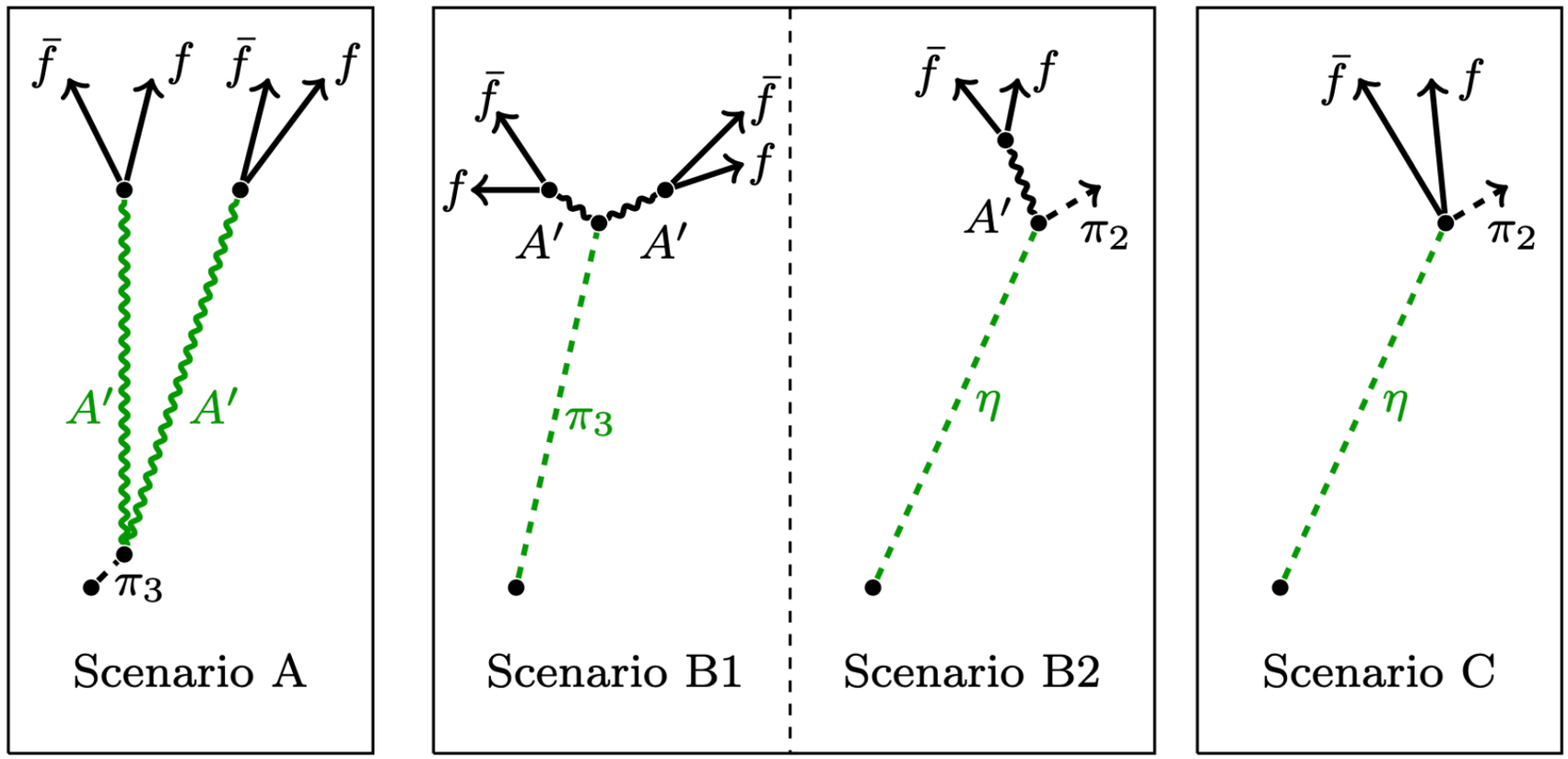


- Also depends on Pythia hadronization choices: `probVector`, `probKeepEta1`

[Born, Karur, Knapen, JS]

DIMUON SIGNATURES

easy → *hard*



high visible multiplicity — low visible multiplicity

[Born, Karur, Knapen, JS]

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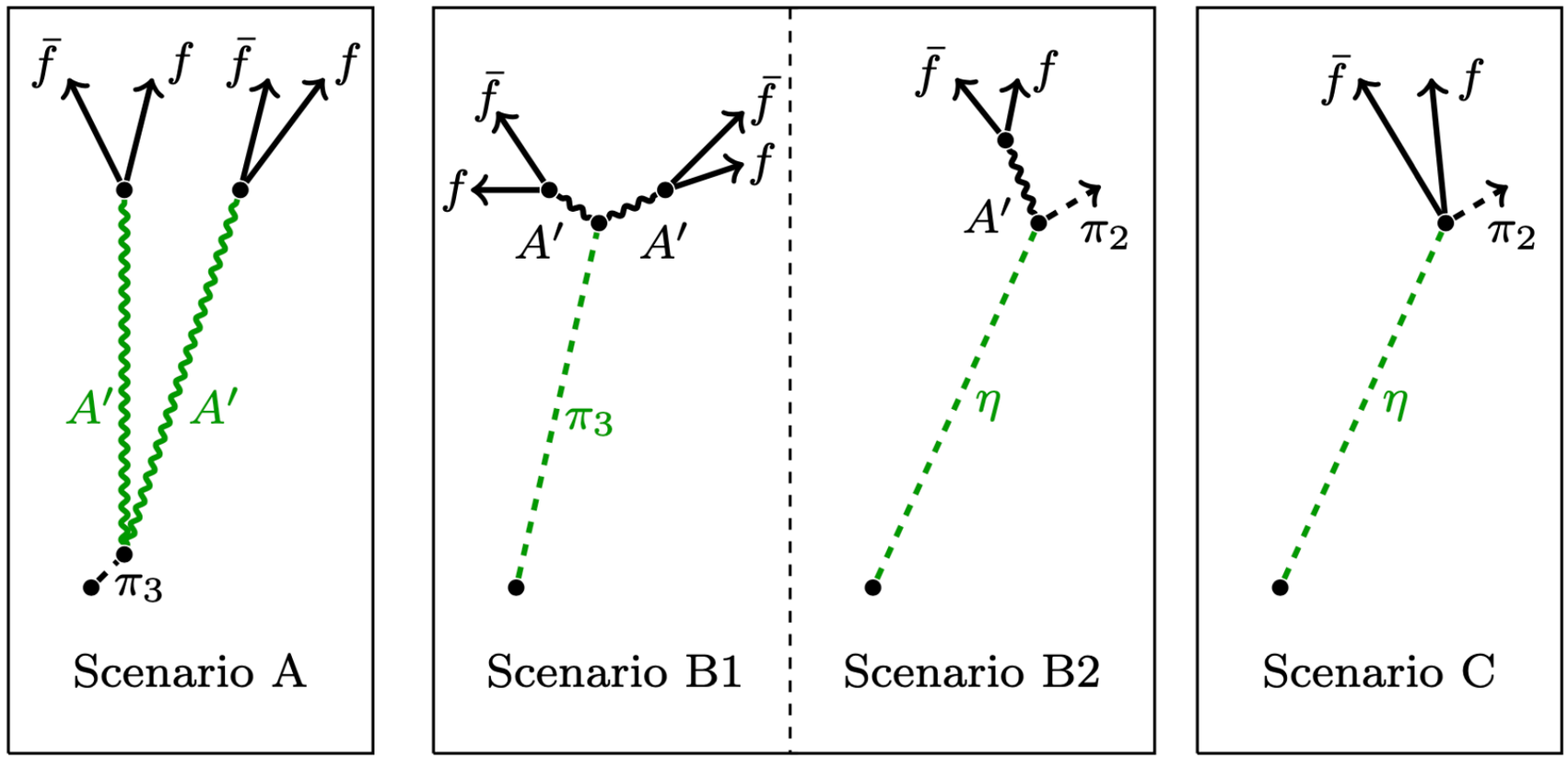

high visible multiplicity — low visible multiplicity

pointing — non-pointing

[Born, Karur, Knapen, JS]

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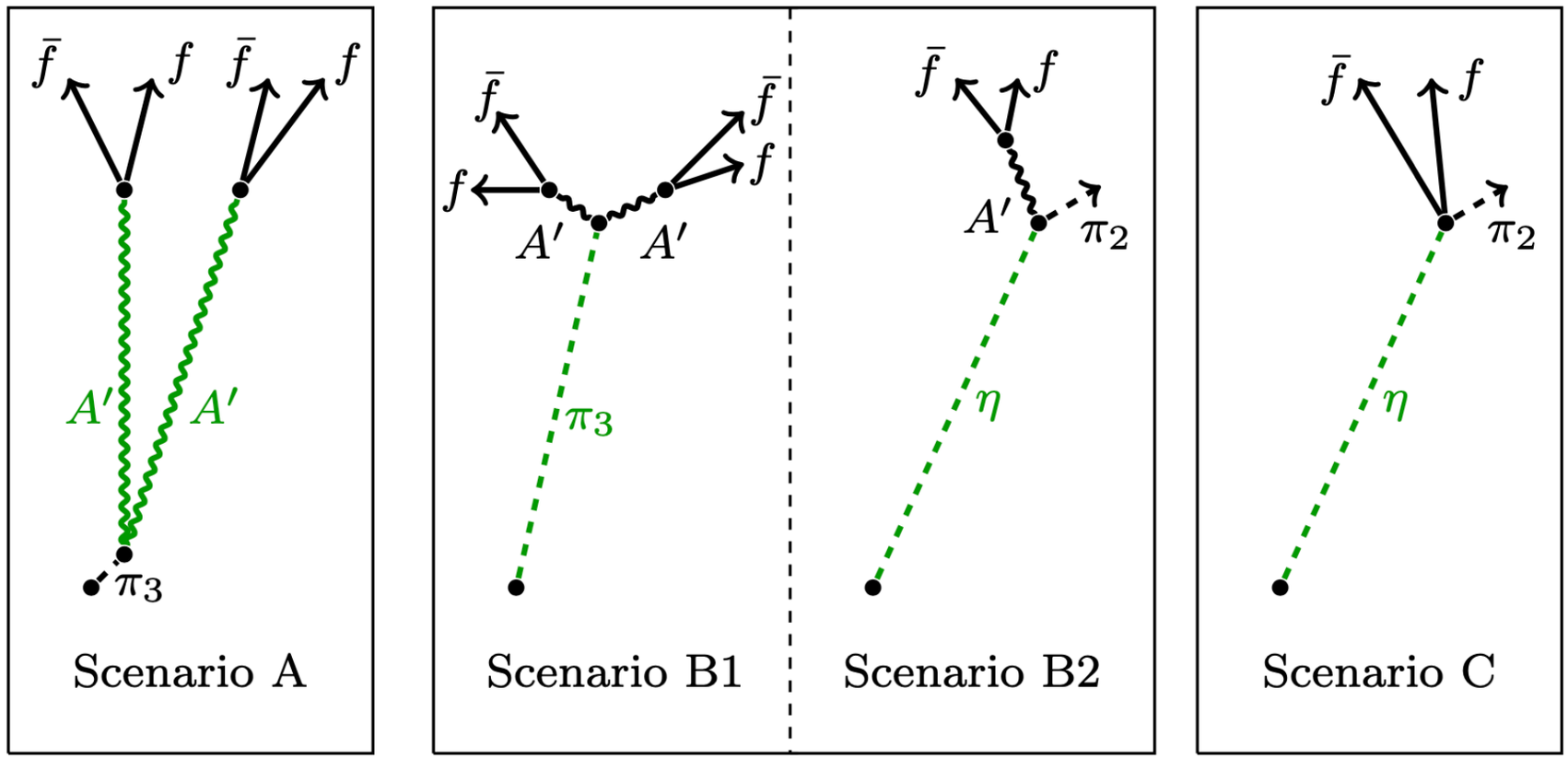


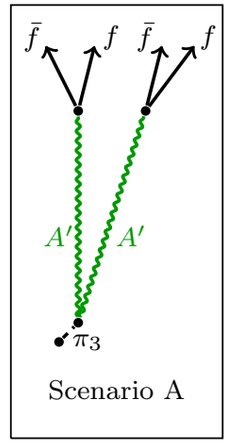
high visible multiplicity — low visible multiplicity

pointing — non-pointing

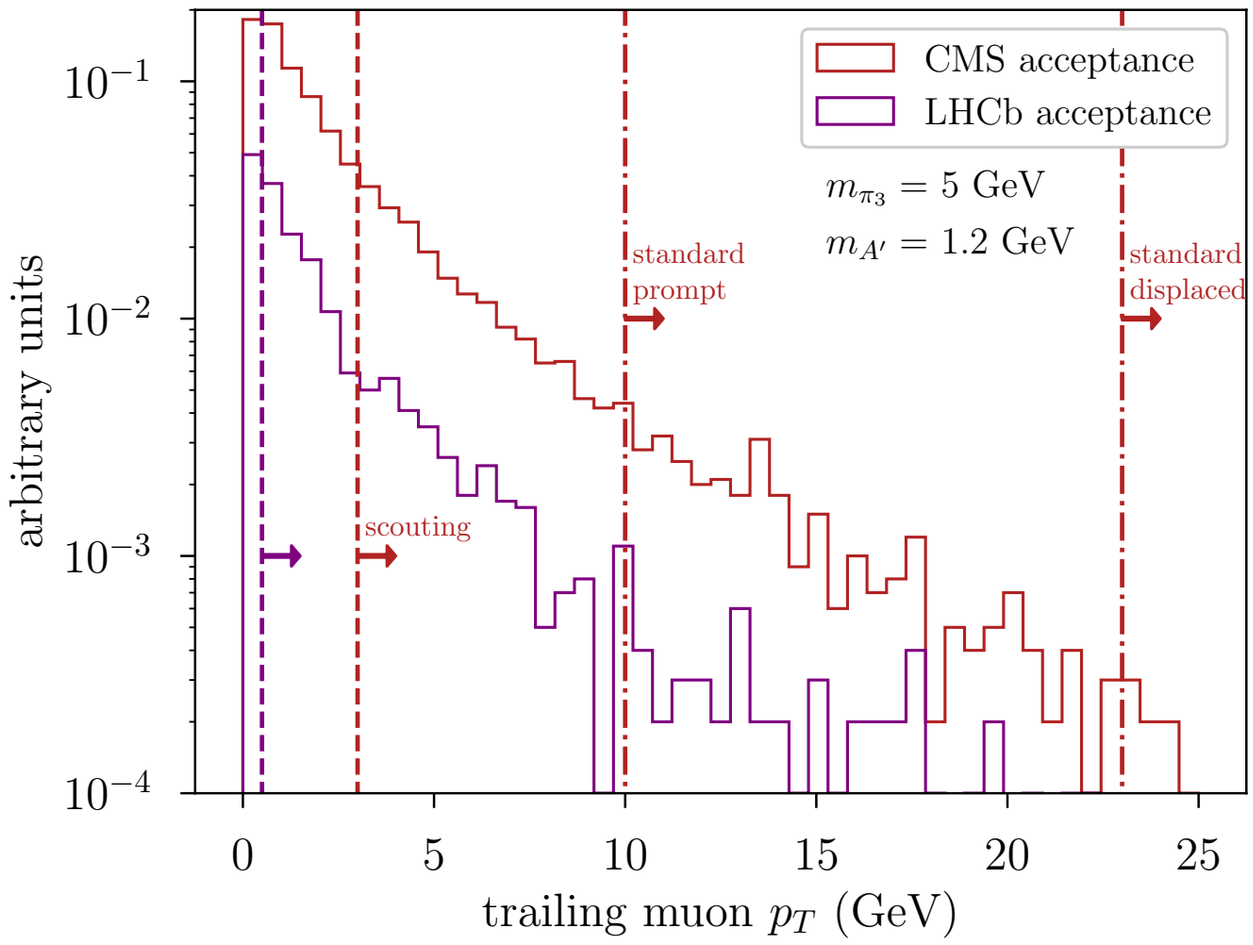
resonant — non-resonant

[Born, Karur, Knapen, JS]

SCOUTING SEARCHES: SCENARIO A



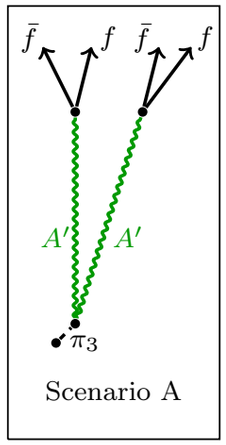
- Searches for resonant, pointing muon pairs:

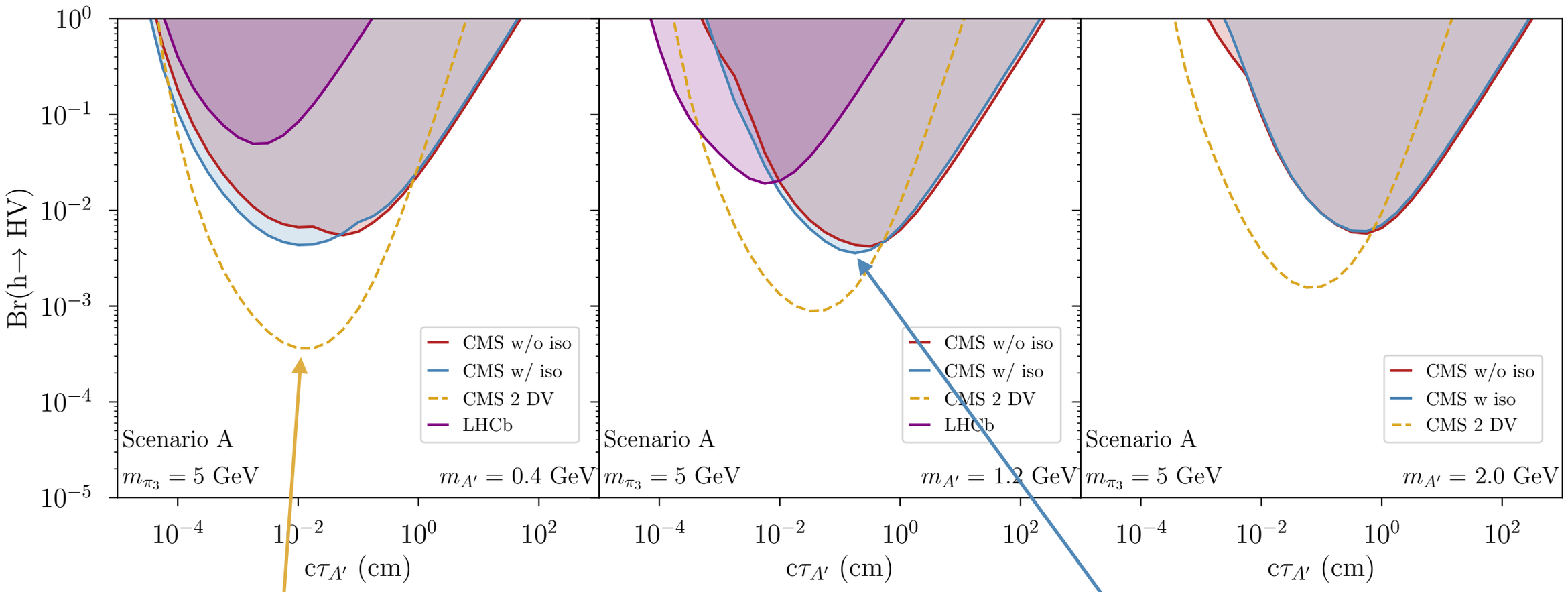


- evaluate reach of displaced CMS scouting, LHCb analyses (results from CMS prompt scouting search also now available)

[Born, Karur, Knapen, JS]

SCOUTING SEARCHES: SCENARIO A



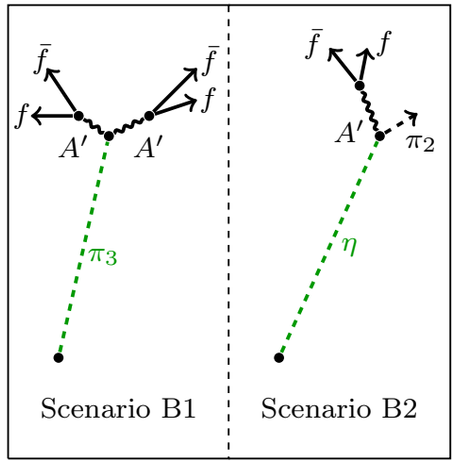


Estimated reach assuming uncorrelated vertex efficiencies, negligible background

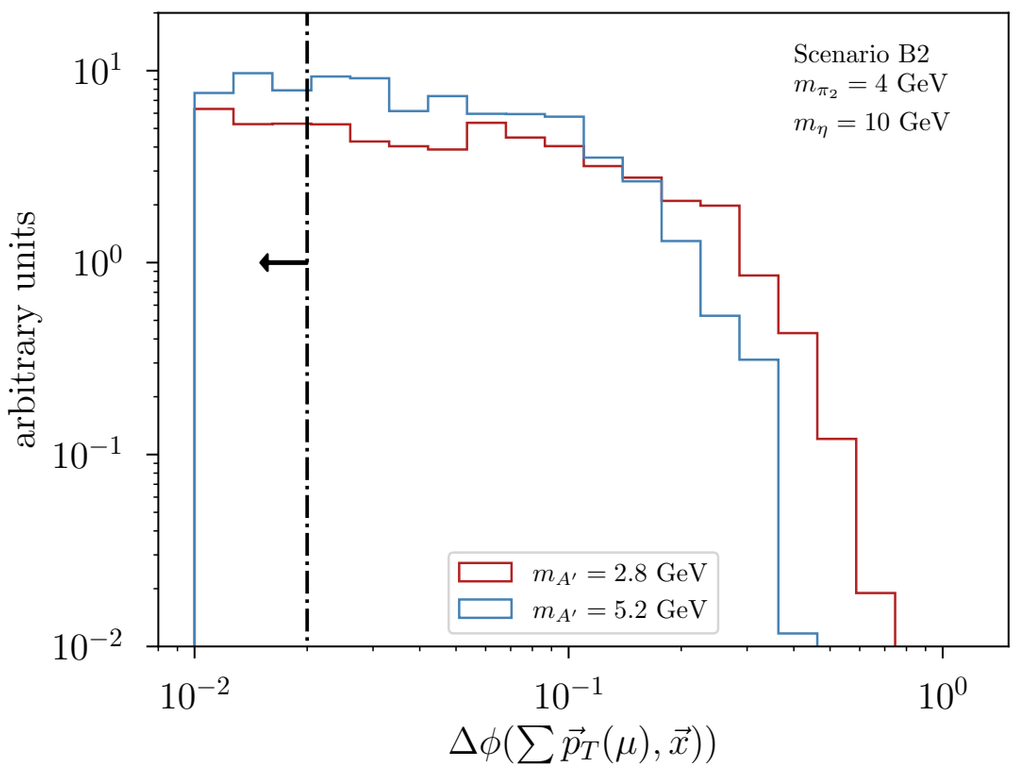
Isolation helps marginally at low dark photon masses; less important at higher masses (not shown)

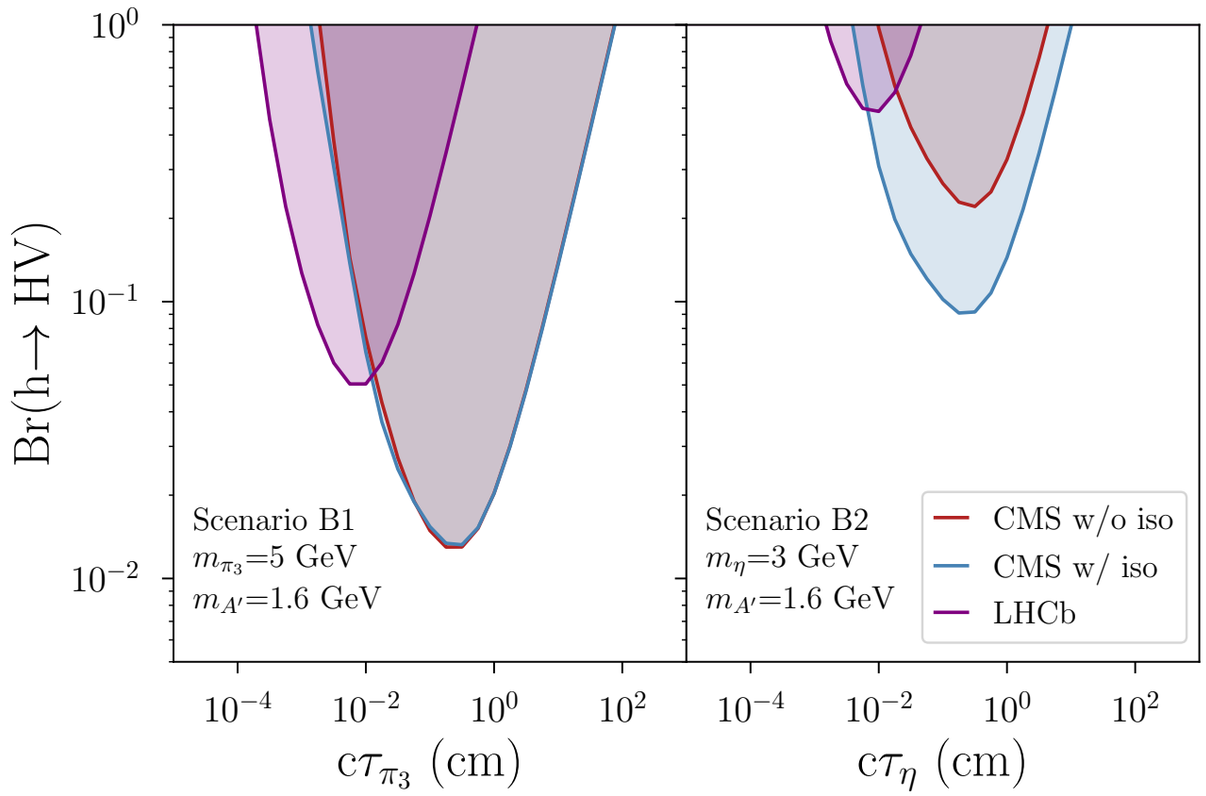
[Born, Karur, Knapen, JS]

SCOUTING SEARCHES: SCENARIO B



- CMS explicitly requires pointing:





- LHCb: inclusive selection, no pointing cut
- B1 vs B2: primary difference is signal multiplicity

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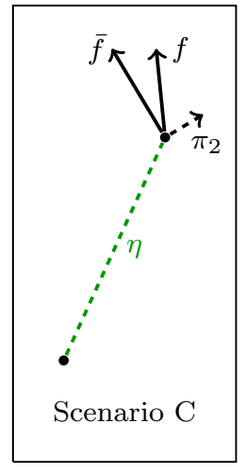
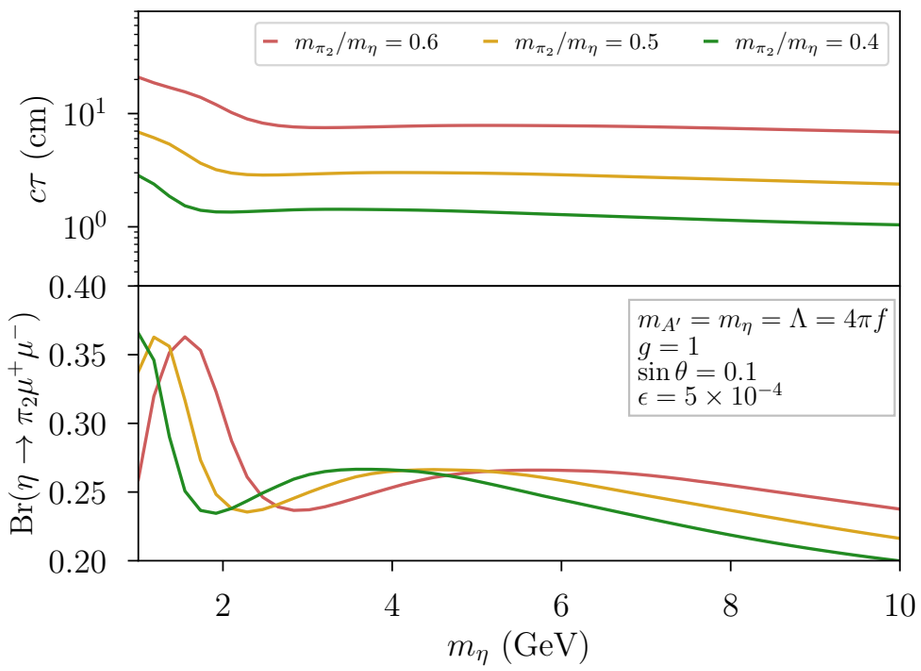
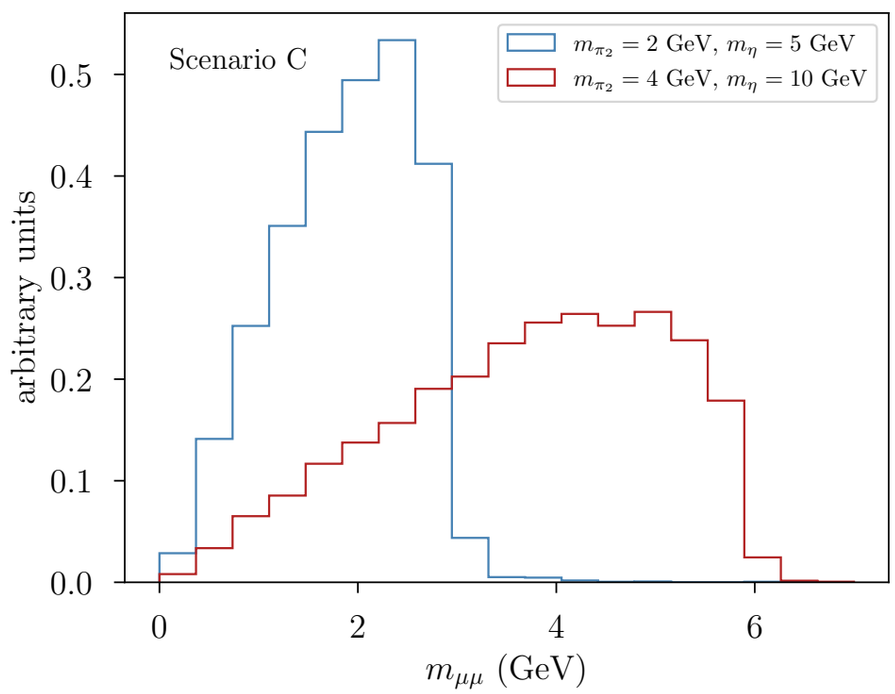
SCOUTING SEARCHES: SCENARIO C



- Challenging scenario, not currently covered
  - always a macroscopic lifetime
  - low-ish signal multiplicity, now spread over multiple dimuon invariant mass bins
  - non-resonant signal complicates background estimation strategy





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SUMMARY AND CONCLUSIONS

- Low-mass dark showers: key signature for maximizing LHC discovery sensitivity
  - Challenging targets, both experimentally and theoretically
- Simplified models: clarify regions of signature space where high-multiplicity search strategies are well-motivated
- Specific model: signature generator for (displaced) low-mass, muon-rich final states; highlight reach of data scouting
  - several suggestions to extend analyses:
    - two vertices
    - non-pointing searches
    - non-resonant, non-pointing