Off the Beaten Track

Unconventional Searches at the LHC

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Rising Stars in Experimental Particle Physics

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Motivation

We all know the Standard Model (SM) isn't the complete picture of the universe

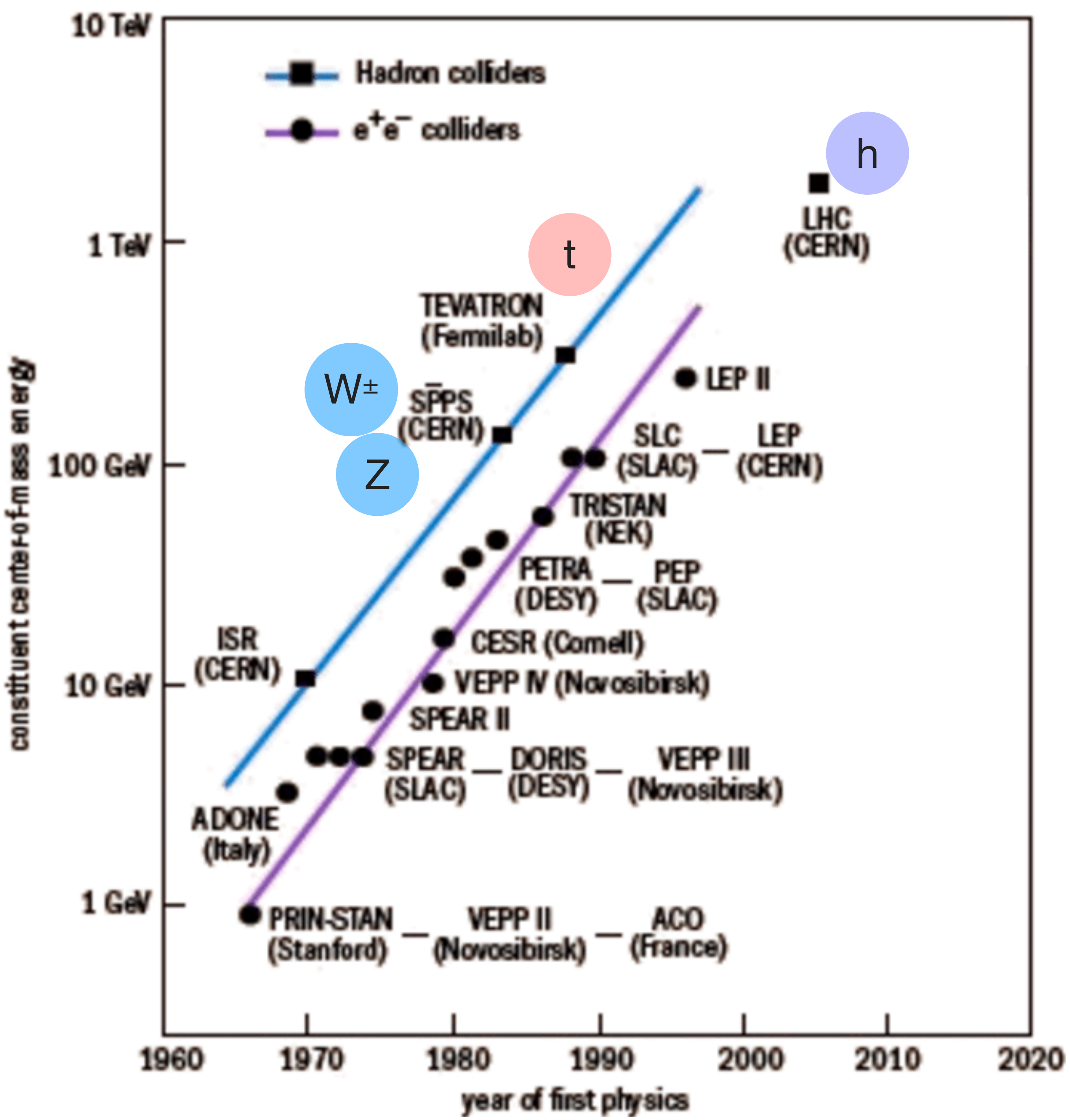
Dark matter exists & is likely a particle

Hierarchy puzzle suggests new particles @TeV scale

Growing list of anomalies (LHCb, muon g-2)

My goal: discover Beyond the Standard Model (BSM) particles at the Large Hadron Collider

High energy colliders



Exciting & effective way to discover new particles

Long history of success!

1985 - W and Z - SppS

1995 - Top Quark - Tevatron

2012 - Higgs Boson - LHC

The LHC phase transition

Run 1					Run 2							Run 3					HL-LHC		
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	…	2036
7/8 TeV 25 fb^{-1}					13 TeV 135 fb^{-1}							13.6 TeV 150 fb^{-1}					14 TeV 3000 fb^{-1}		

increase in energy

mass reach ~ energy

increase in luminosity, L

for a fixed mass: probing smaller Cross Section x Branching Ratio

significance ~ $\sqrt{L}$ or L

What this means for LHC physicists

Unprecedented LHC luminosity = unique opportunity

Standard Model: access rare processes & precision measurements

Powerful (indirect) probes of new physics

Paradigm shift for BSM searches: new emphasis on signatures which may have evaded detection

Low cross sections, low efficiency, and/or challenging backgrounds

Or we simply haven't looked before

My opinion: if we're producing BSM particles at the LHC we need to make sure we don't miss them

What have we looked for?

LHC searches typically assume

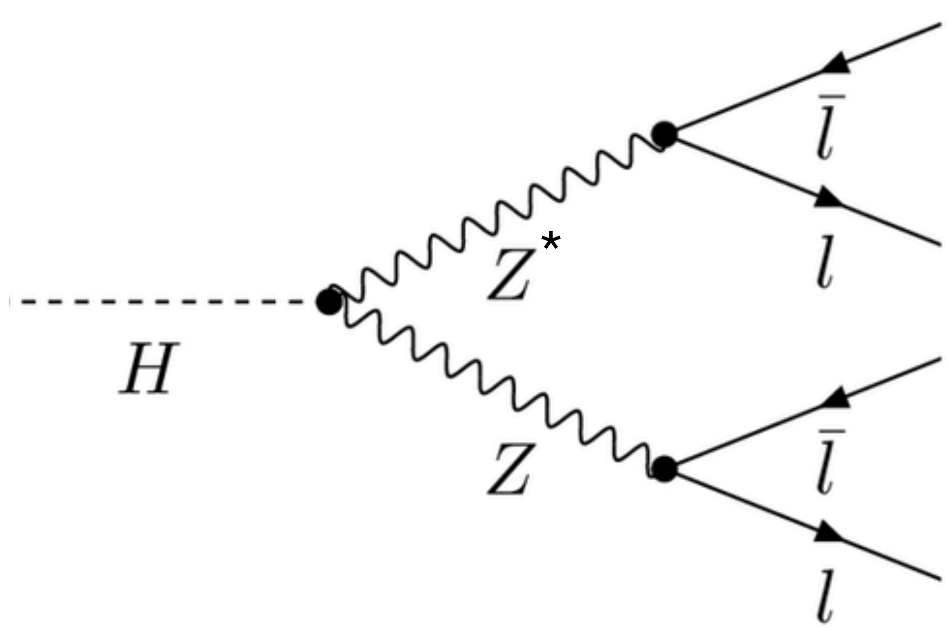
new heavy particles decay promptly to high momentum SM particles

dark matter particles are stable & non-interacting

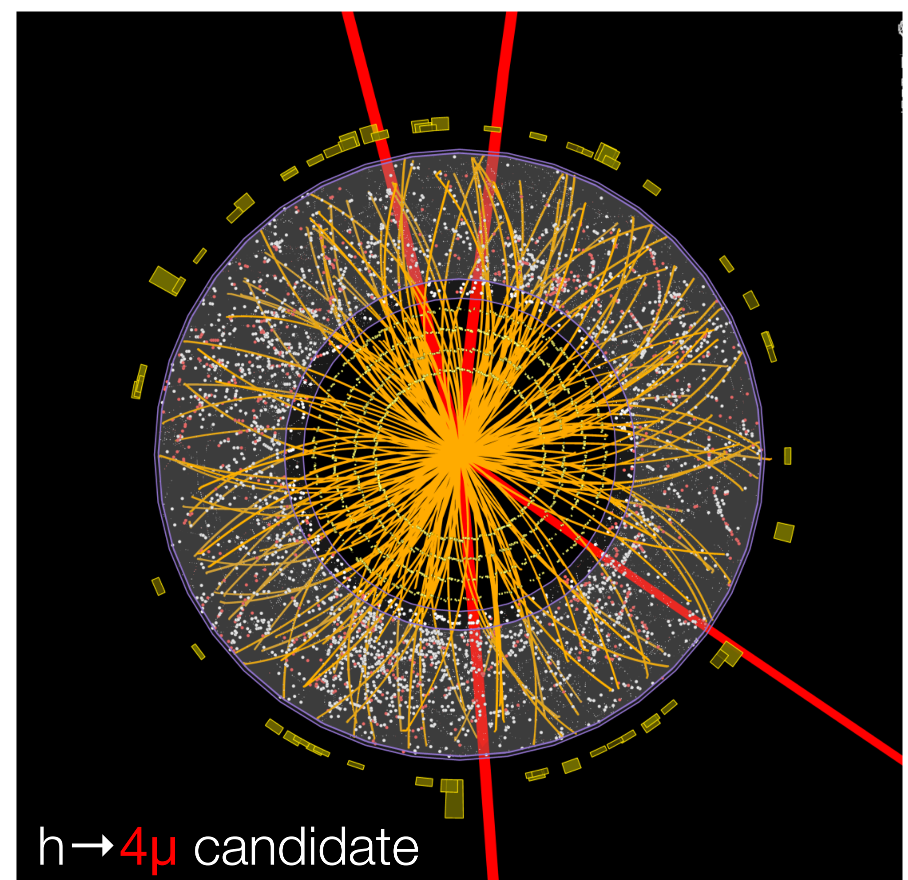
Historically this has been a good assumption

eg. W, Z, higgs, and top lifetimes < 10^{-20} s

cannot resolve decay from point of production



Higgs Golden Channel



Detector Design

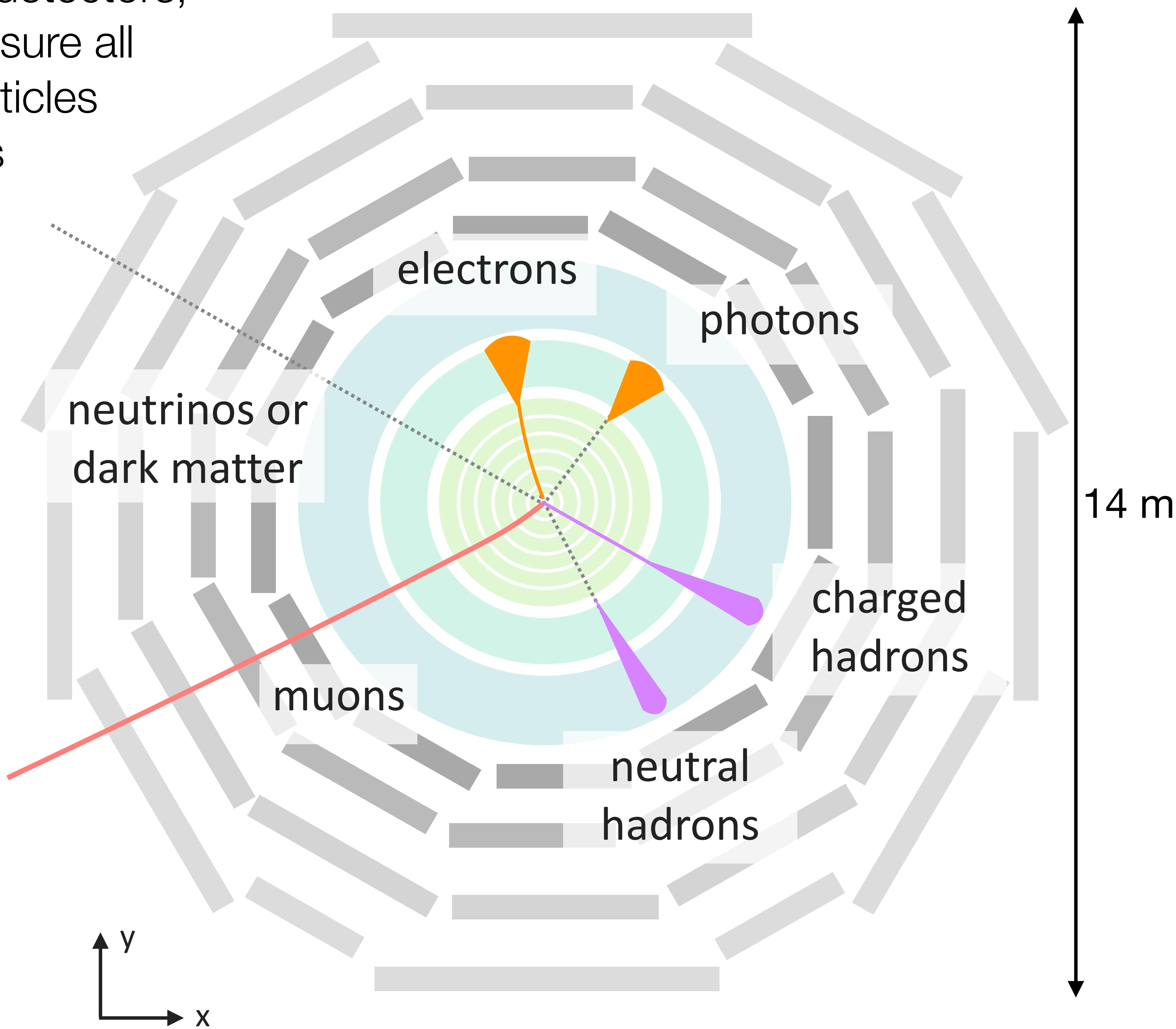
ATLAS & CMS: cylindrical detectors, designed to identify & measure all stable Standard Model particles produced in LHC collisions

Inner Detector

Electromagnetic Calorimeter

Hadronic Calorimeter

Muon Spectrometer



Detector Design

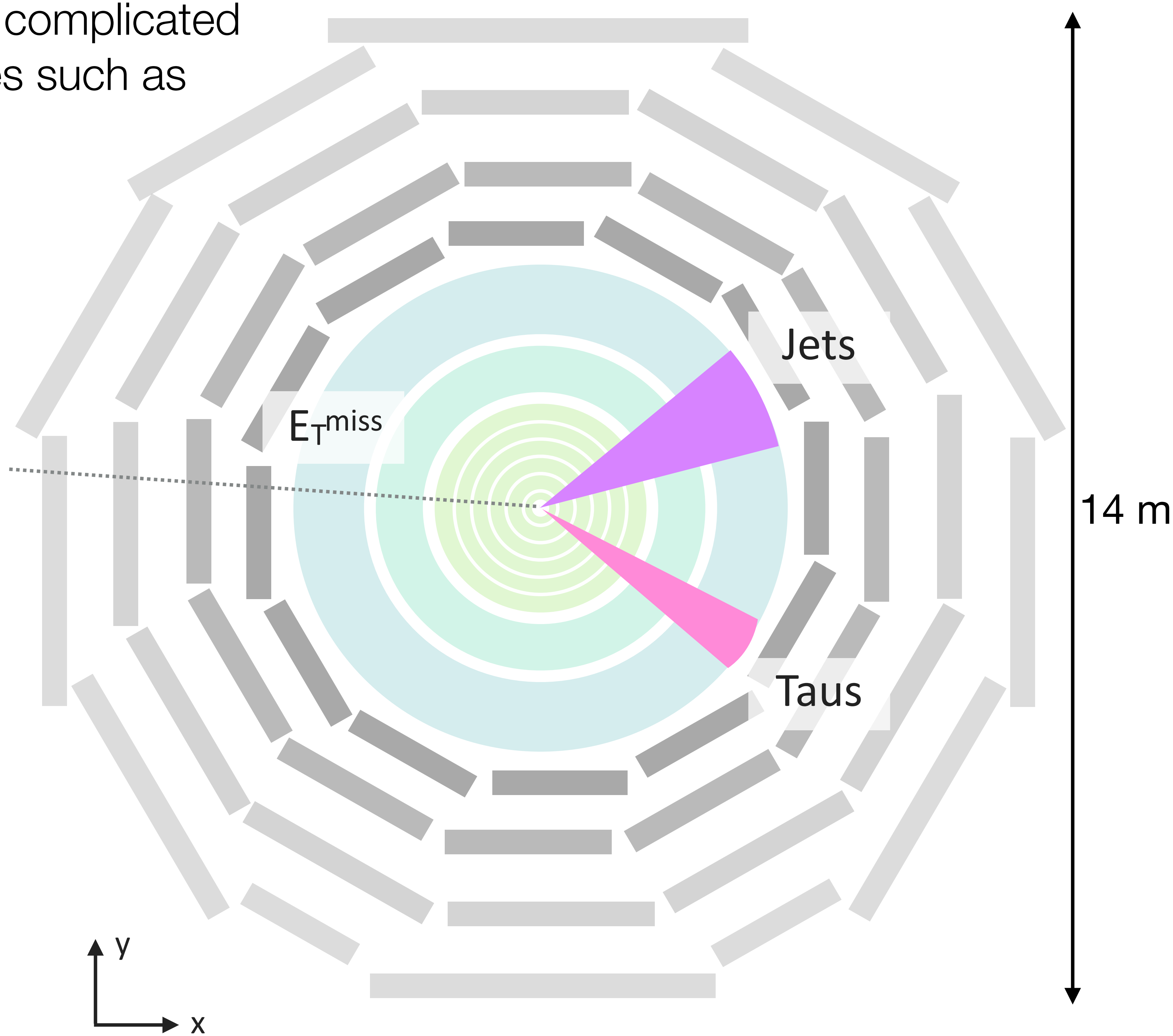
And we can build up more complicated objects and event quantities such as jets/taus/E_T^{miss}

Inner Detector

Electromagnetic Calorimeter

Hadronic Calorimeter

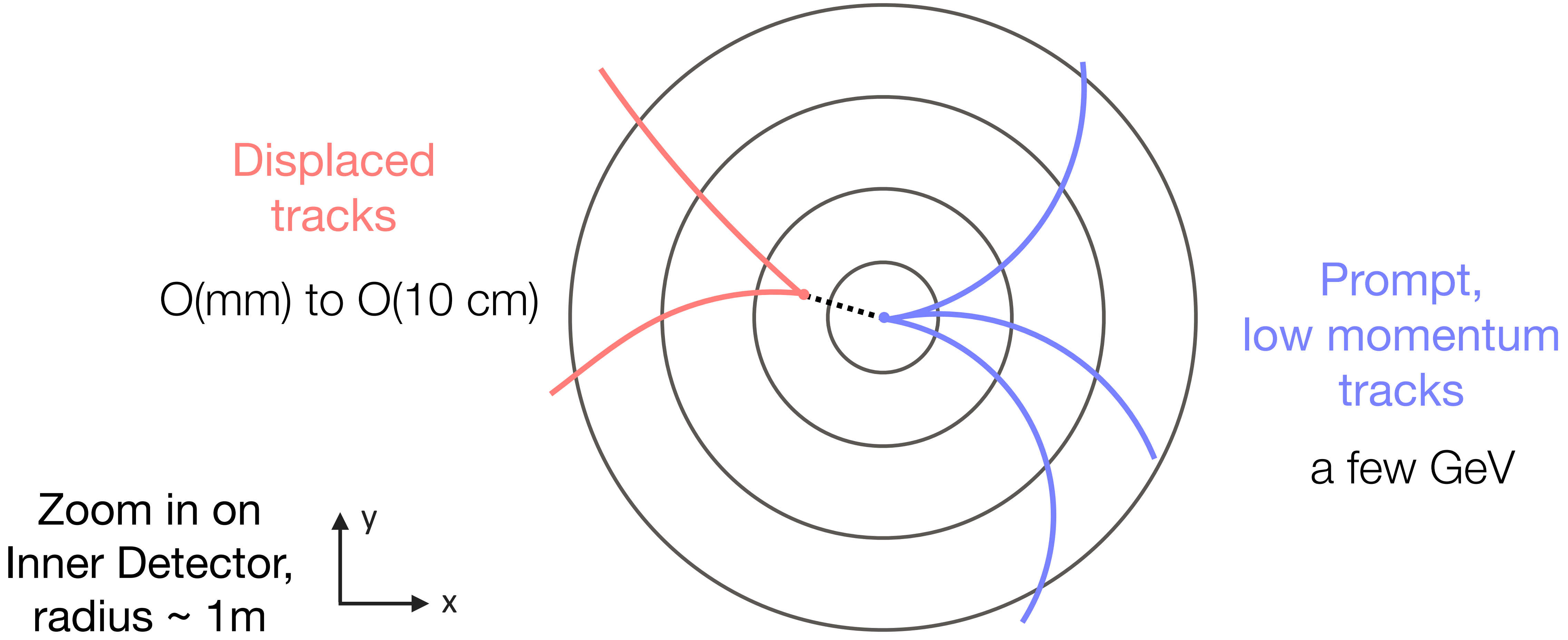
Muon Spectrometer



What is uncovered?

Signatures with unconventional tracks

New long-lived particles (LLPs) that result in displaced decays
Or new particles that result in low momentum (soft) decay products



Unconventional Motivation

Event though these signatures are “unconventional” displaced and soft tracks are well motivated

Lifetime

$$\tau^{-1} = \Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

y - small couplings
M ≫ m - hierarchy of scales
eg. SM weak decays

Momentum

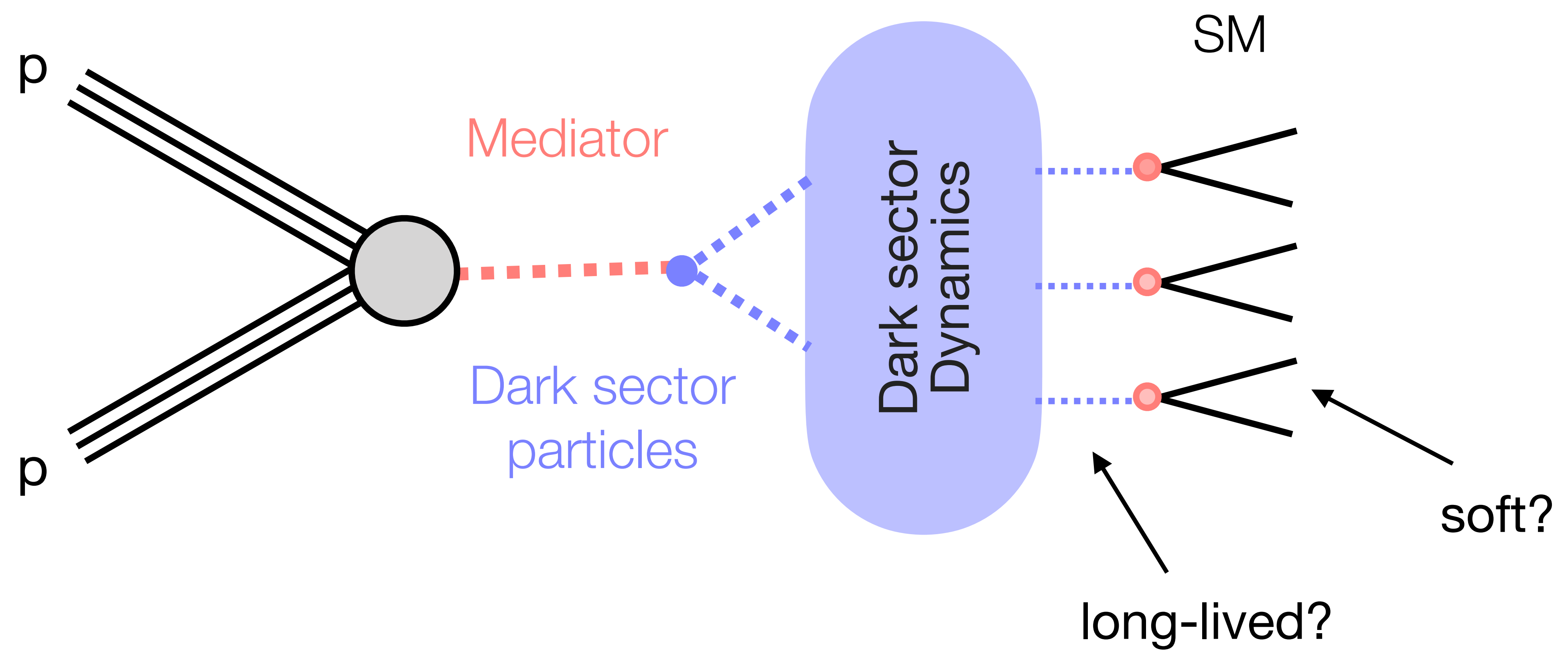
$$p \sim \frac{\text{phase space}}{\text{N decay products}}$$

Lower mass mediators
Small mass splittings
High multiplicity of decay products

Commonly appear in your favorite Supersymmetry or hidden valley models

Unconventional Motivation

The examples I'll use are hidden valley scenarios



Diverse range of possible phenomenologies, experimental coverage = to be improved!

Major challenge: the trigger

Why can't you just modify your reconstruction?

Need to make sure our events are saved to disk first!

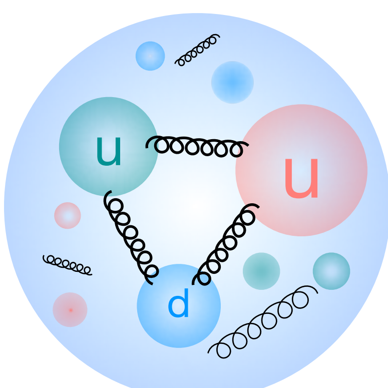
2. LHC over produces collisions

~billion mostly soft collisions/second

~1/second is a higgs

1. Protons are

composite particles



3. We cannot save all our collisions

Event size: 1-2 MB

Produce: O(10) TB/s

Limited by bandwidth & storage

The trigger: decides which ~1 in 10^5 collisions we can keep

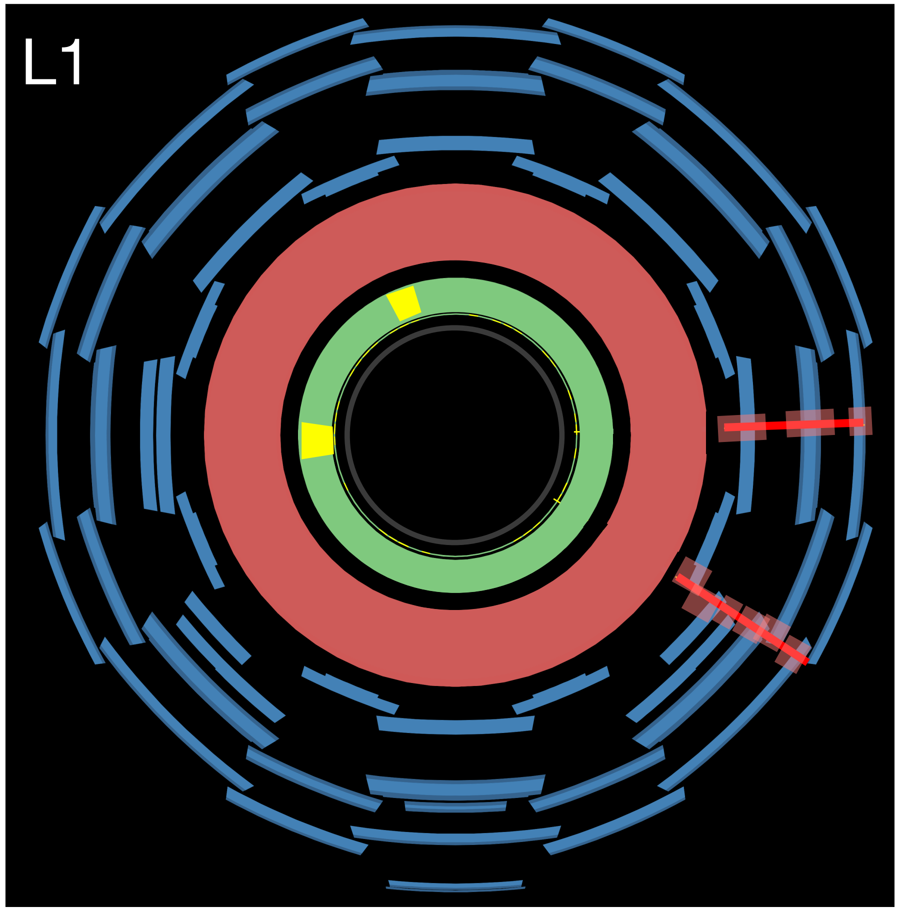
High stakes decision made in real time

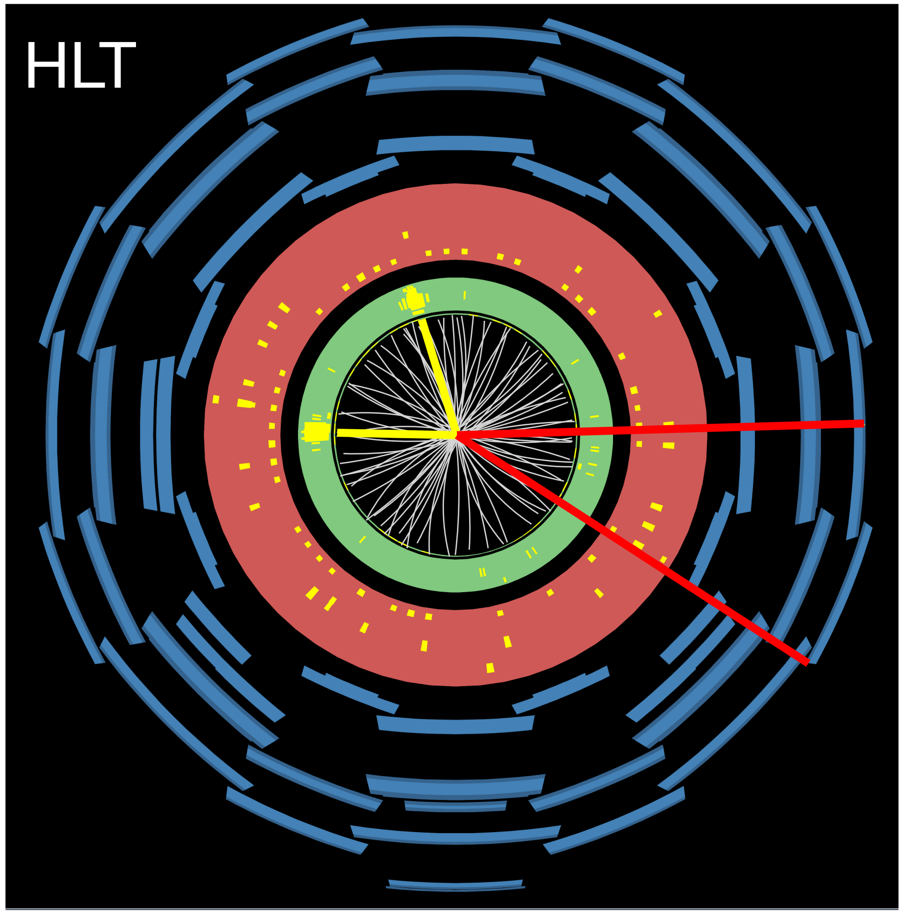
How the trigger works

Targets prompt high p_T objects in a two step process

Level 1 (L1): coarse calorimeter & muon information

High Level Trigger (HLT): refines & add limited tracking information





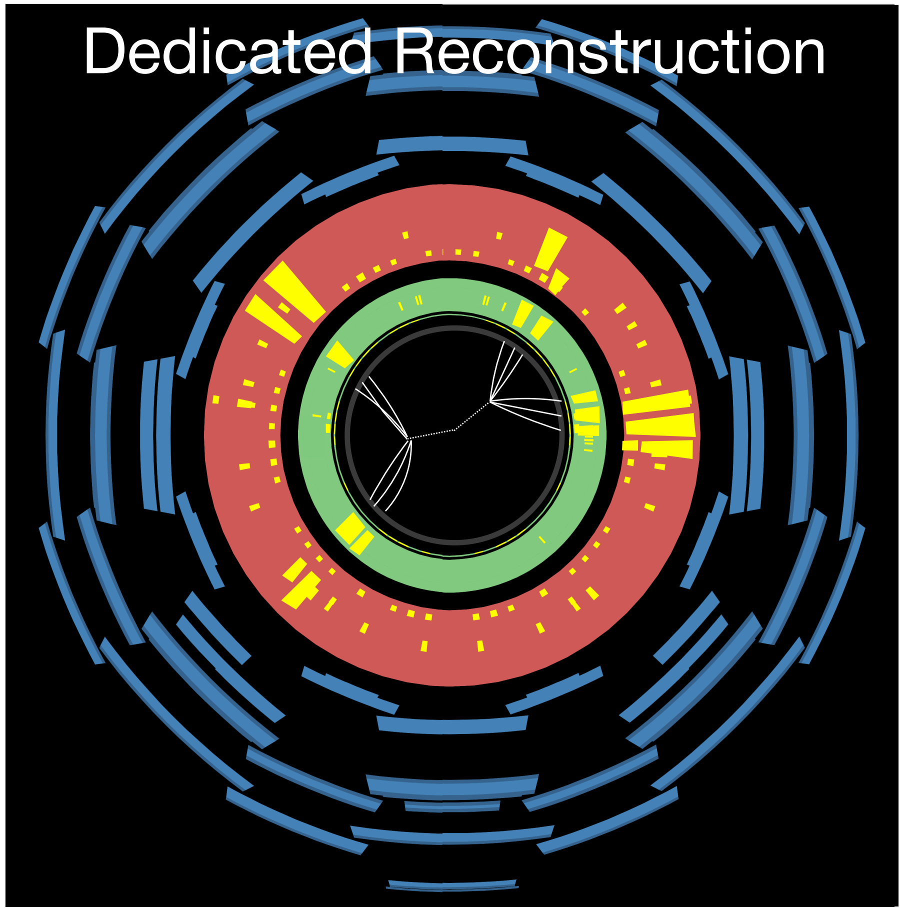
Works very well for Standard Model processes & prompt searches

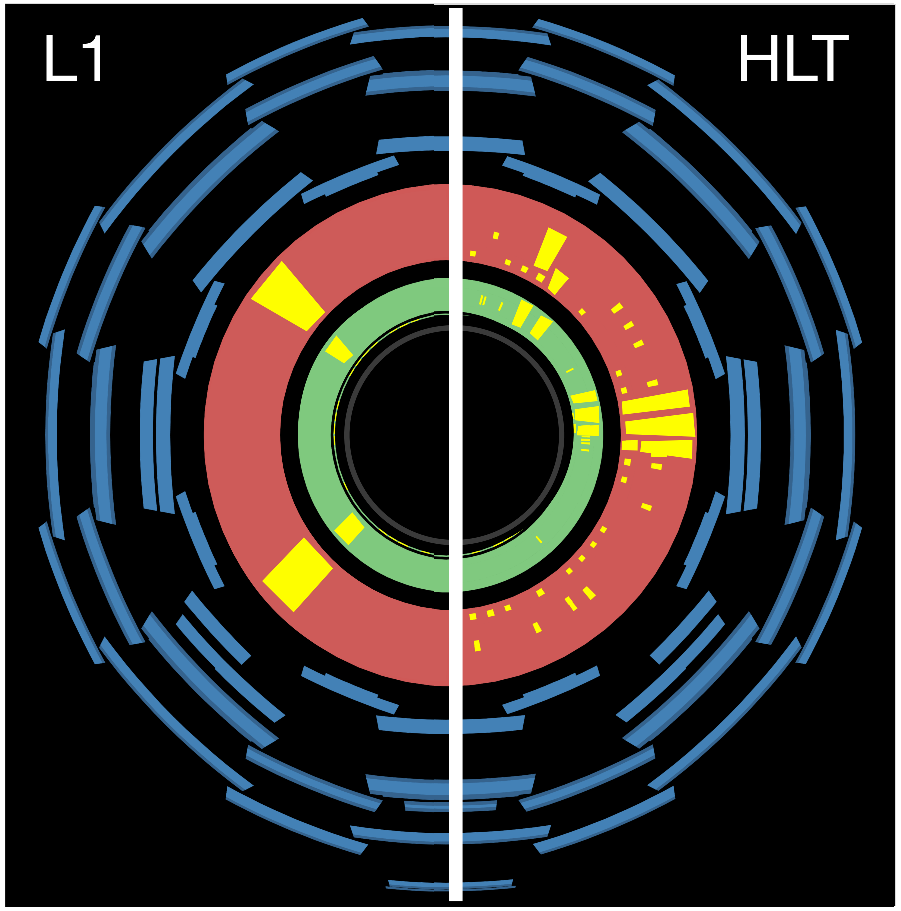
eg. higgs→ZZ*→2e2μ

What the trigger can't do (yet)

Consider: higgs → XX → 4 jets, where X is long-lived

Difficult for trigger to distinguish from QCD background





Low efficiency when tracks are the most conspicuous feature!

So what can we do?

Run 1	Run 2	Run 3	HL-LHC
2011 2012 2013 2014	2015 2016 2017 2018 2019 2020 2021	2022 2023 2024 2025 2026 2027	2028 … 2036
7/8 TeV, 25 fb^{-1}	13 TeV, 135 fb^{-1}	13.6 TeV, 150 fb^{-1}	14 TeV, 3000 fb^{-1}

Run 2: Use existing triggers in most recent dataset

Run 3: Design new triggers with limited tracking information available

HL-LHC: Upgrade detector & trigger scheme

So what can we do?

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Run 2: Use existing triggers in most recent dataset ⟵ *soft-track example*

Run 3: Design new triggers with limited tracking information available

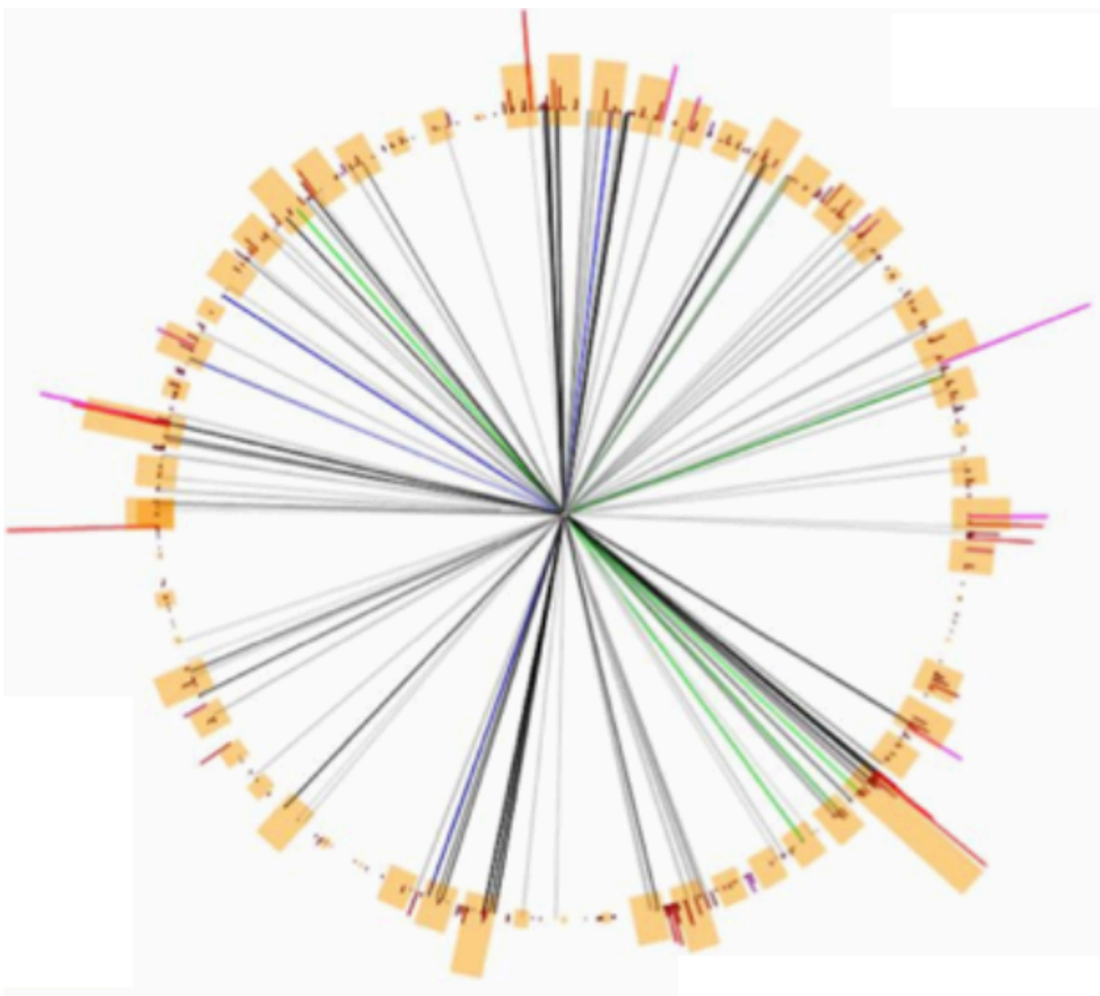
HL-LHC: Upgrade detector & trigger scheme ⟵ *displaced-track example*

A soft track example

SUEPs = soft unclustered energy patterns

Predicted in models with a dark QCD sector and large t'Hooft coupling

Spherical event shape, large multiplicity of low momentum particles



Evades previous searches because final state particles aren't collimated into high p_T QCD-like jets

Considered impossible for LHC triggers by community

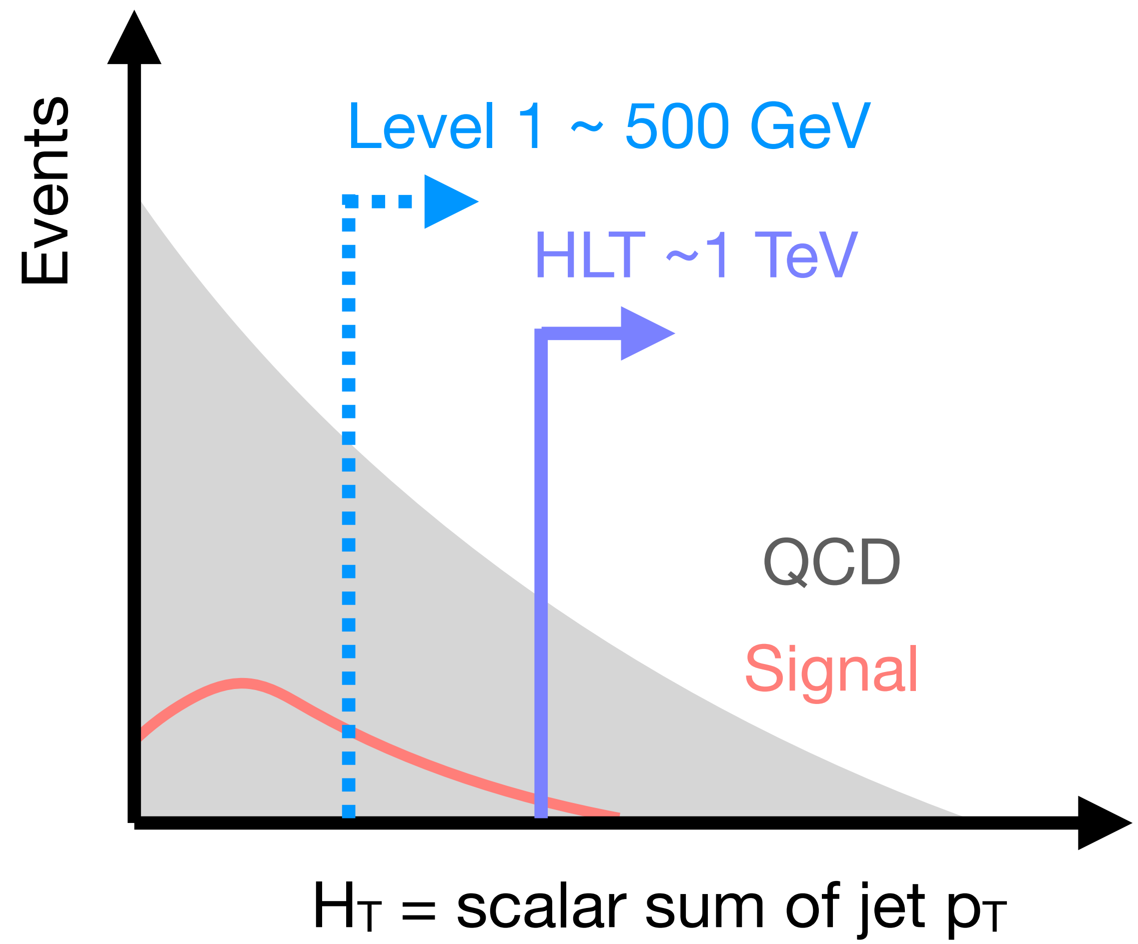
Bonus: dark QCD models have nice possibilities

Dark matter = lightest baryon? Colorless top partner?

Turns out we were wrong

Existing triggers perform much better than expected

All we needed to do was try!



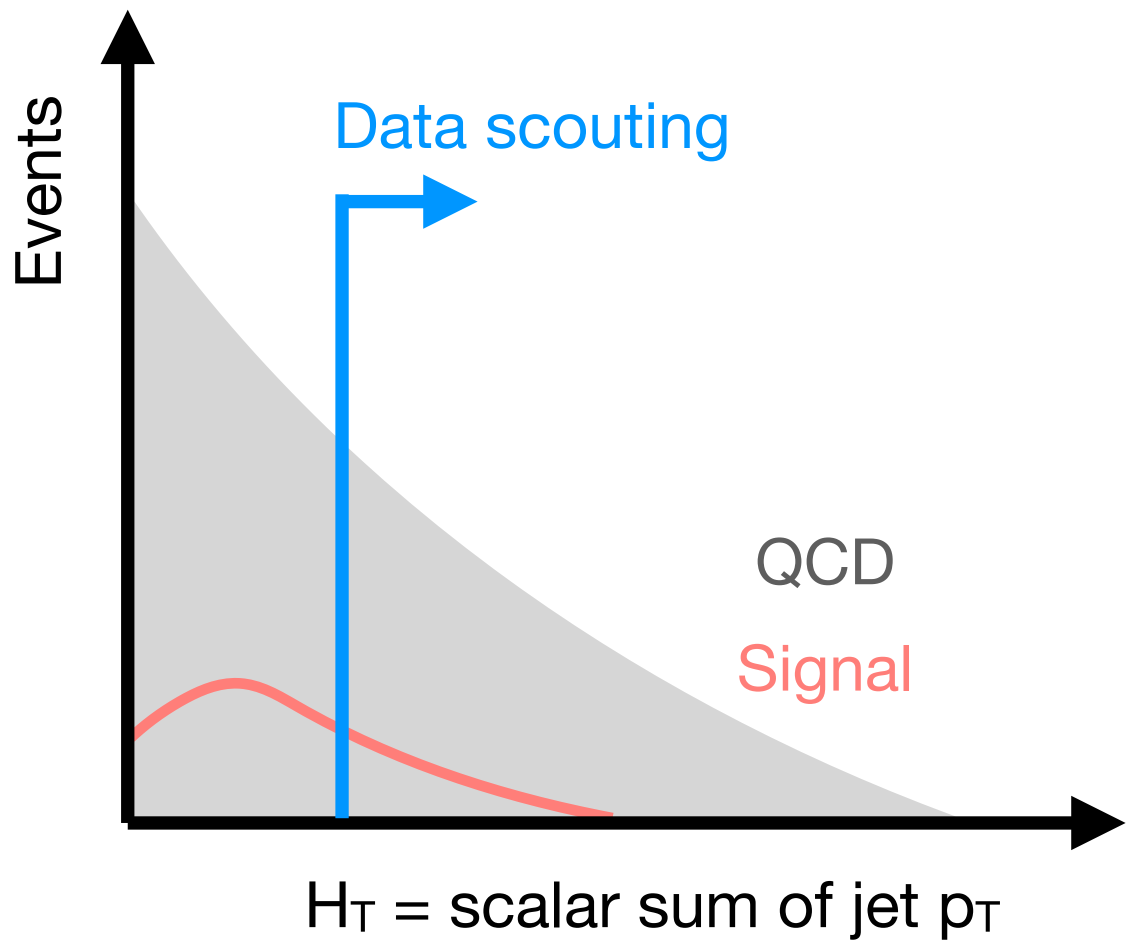
Level 1
O(10) % efficiency

High Level Trigger
O(1)% efficiency

This strategy applies to most models with unconventional signatures
It's often good enough to do an analysis!

Turns out we were wrong

Bonus: In CMS we have an additional trick called "data scouting"



Save events passing Level 1

<u>Bandwidth trade-off</u>: Can only store reduced event content

Includes, momentum vectors of all prompt tracks with $p_T > 0.6$ GeV

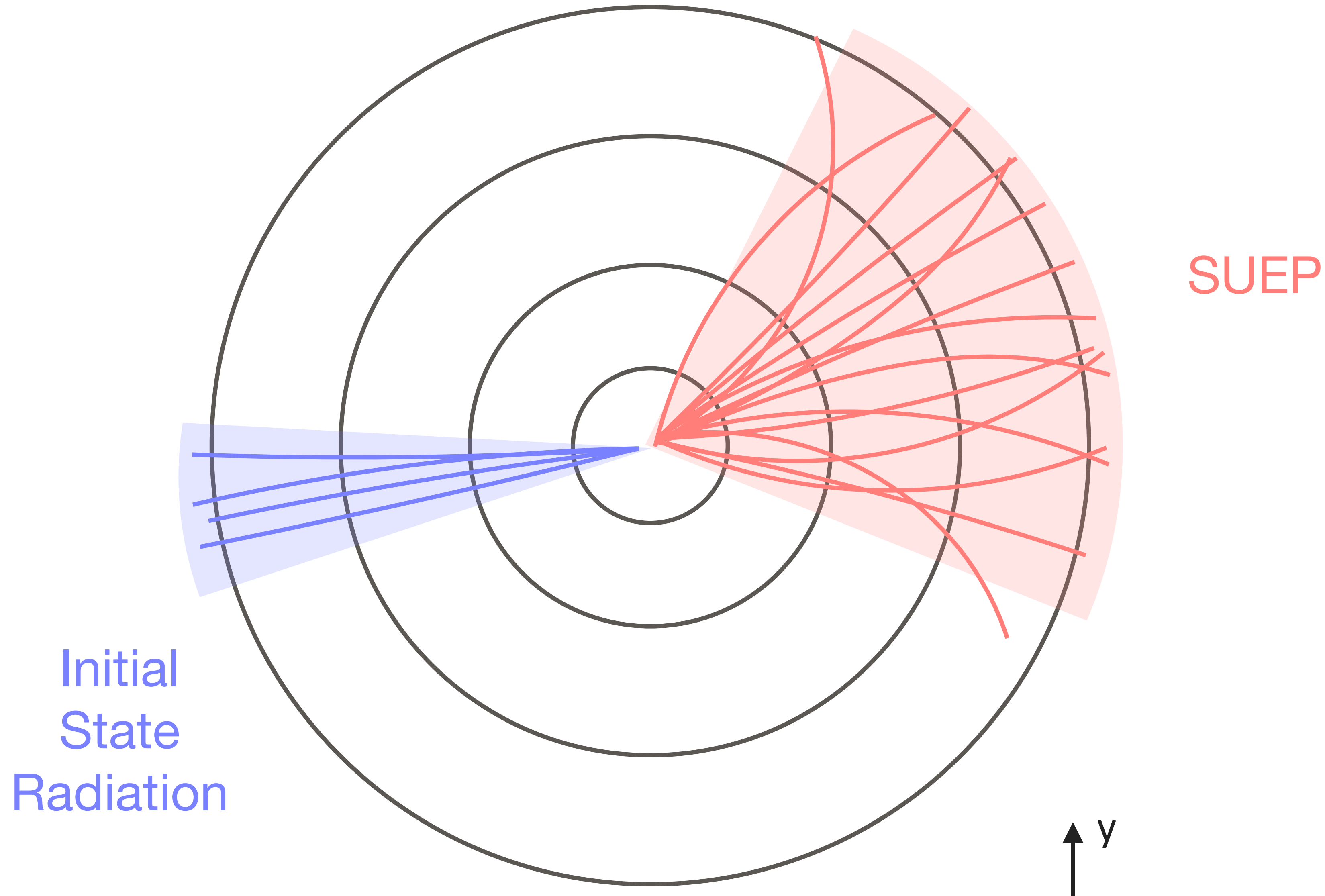
Data scouting leaves us with

O(10) billion background events and ~10k-100k signal events

Analysis strategy

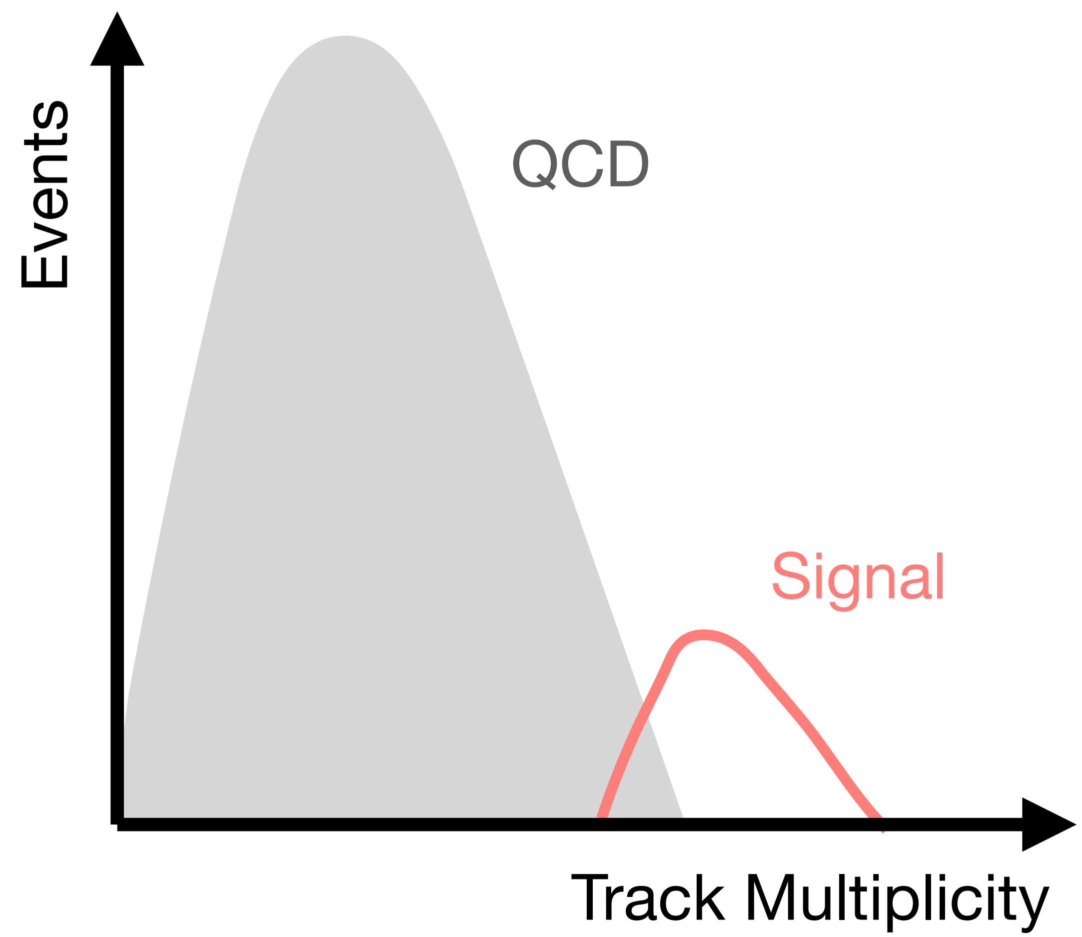
Resulting SUEP events are highly boosted

Recover isotropic event shape by boosting into rest frame



Analysis strategy

Most powerful discriminant: track multiplicity



Run 2: First discovery potential for wide range of SUEP phase space!

A displaced track example

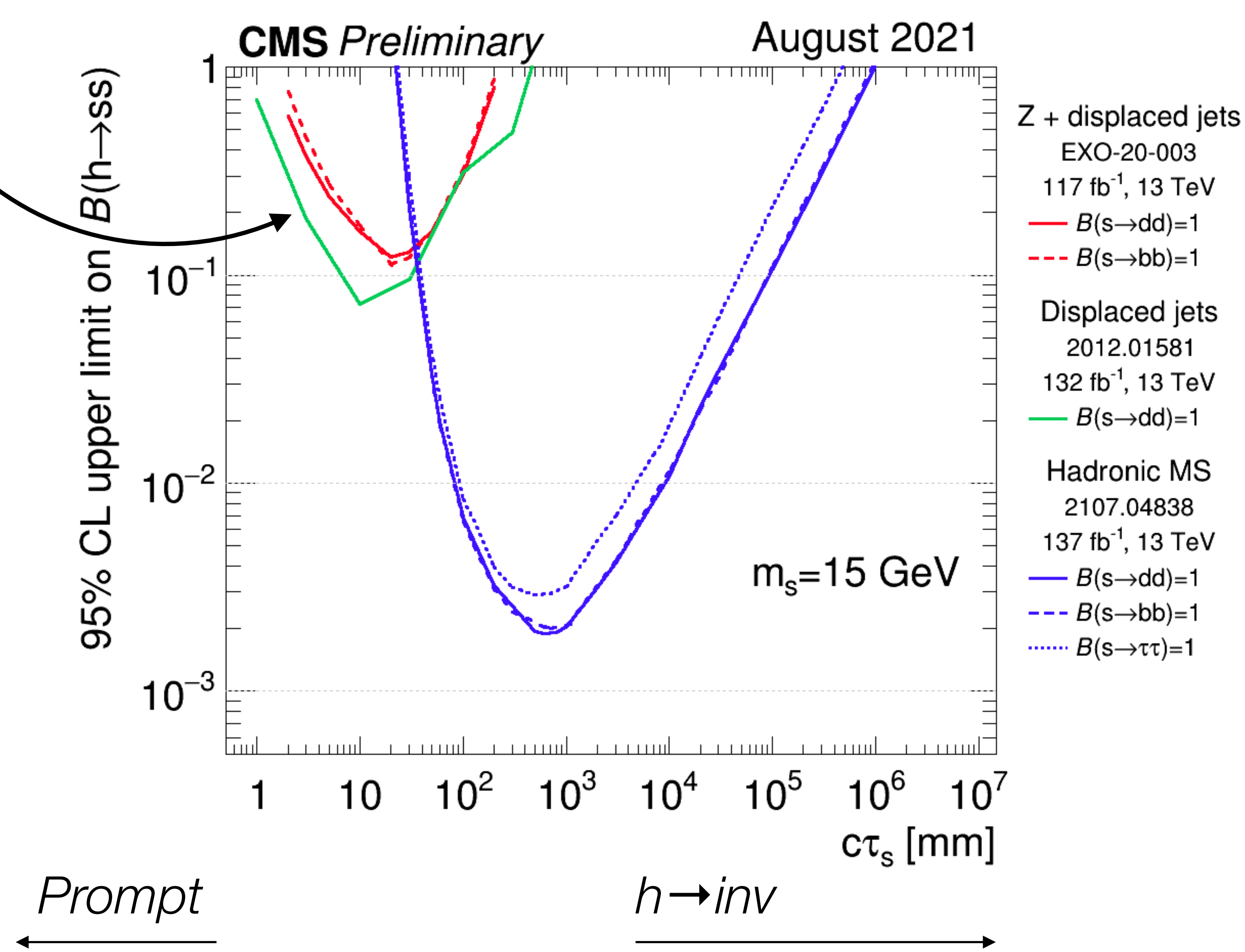
Motivation: higgs → XX → 4b

Well known blind spot in LHC coverage for $c\tau_X$ ~ 1 cm

Two CMS Run 2 analyses targeting this gap

Different trigger strategies
Inclusive displaced jets (H_T)
Z+displaced jets (single lepton)

Resulting sensitivity
Br(h) ~ 10^{-1} to 10^{-2}
Better for larger m_X



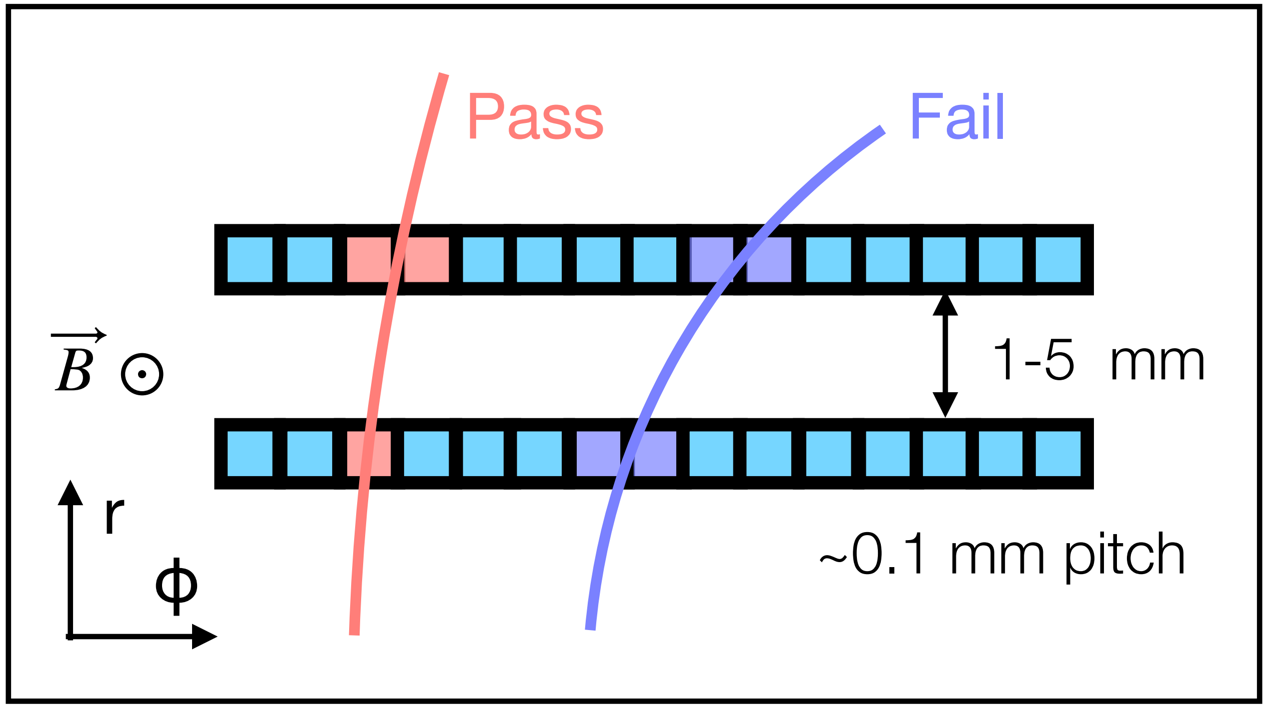
Future prospects

In the near term: both ATLAS and CMS have ongoing efforts to systematically improve coverage with existing capabilities

In the longer term: major upgrades to our detector and trigger

CMS will have tracking information at Level 1 for the first time!

CMS Tracker p_T-module Concept



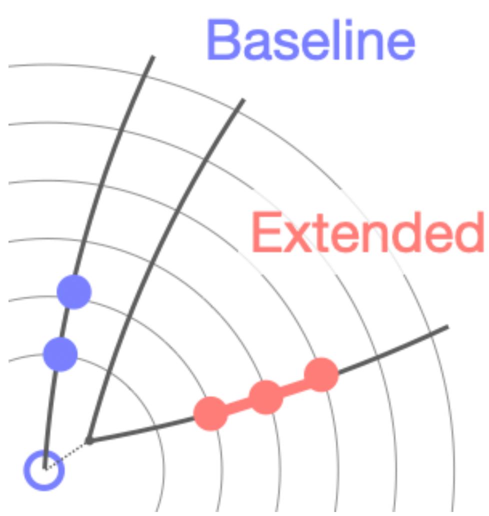
Only readout hits compatible with $p_T > 2$ GeV particles (stubs)

At Level 1 reconstruct all *prompt* tracks with $p_T > 2$ GeV

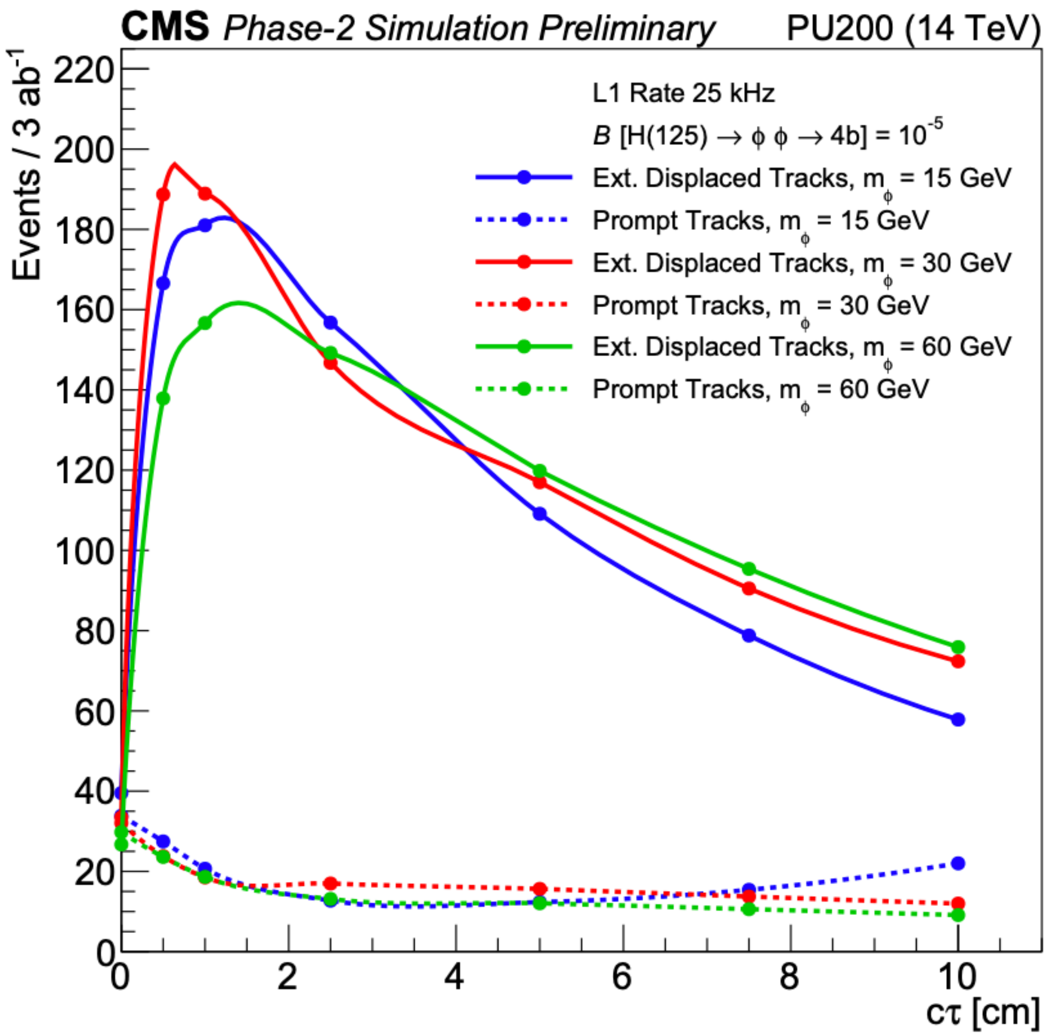
Exciting possibilities

In the works: possibility to extend the track trigger to larger displacements (few cm)

Track finding: 3 stubs instead of 2 + primary vertex



Track fitting: unconstrained transverse impact parameter



Displaced tracking at Level 1 could improve sensitivity to Br(h) by several orders of magnitude

Conclusions

We expect new physics at LHC energy scale,
but haven't seen it yet

New physics could be hiding in existing & future datasets

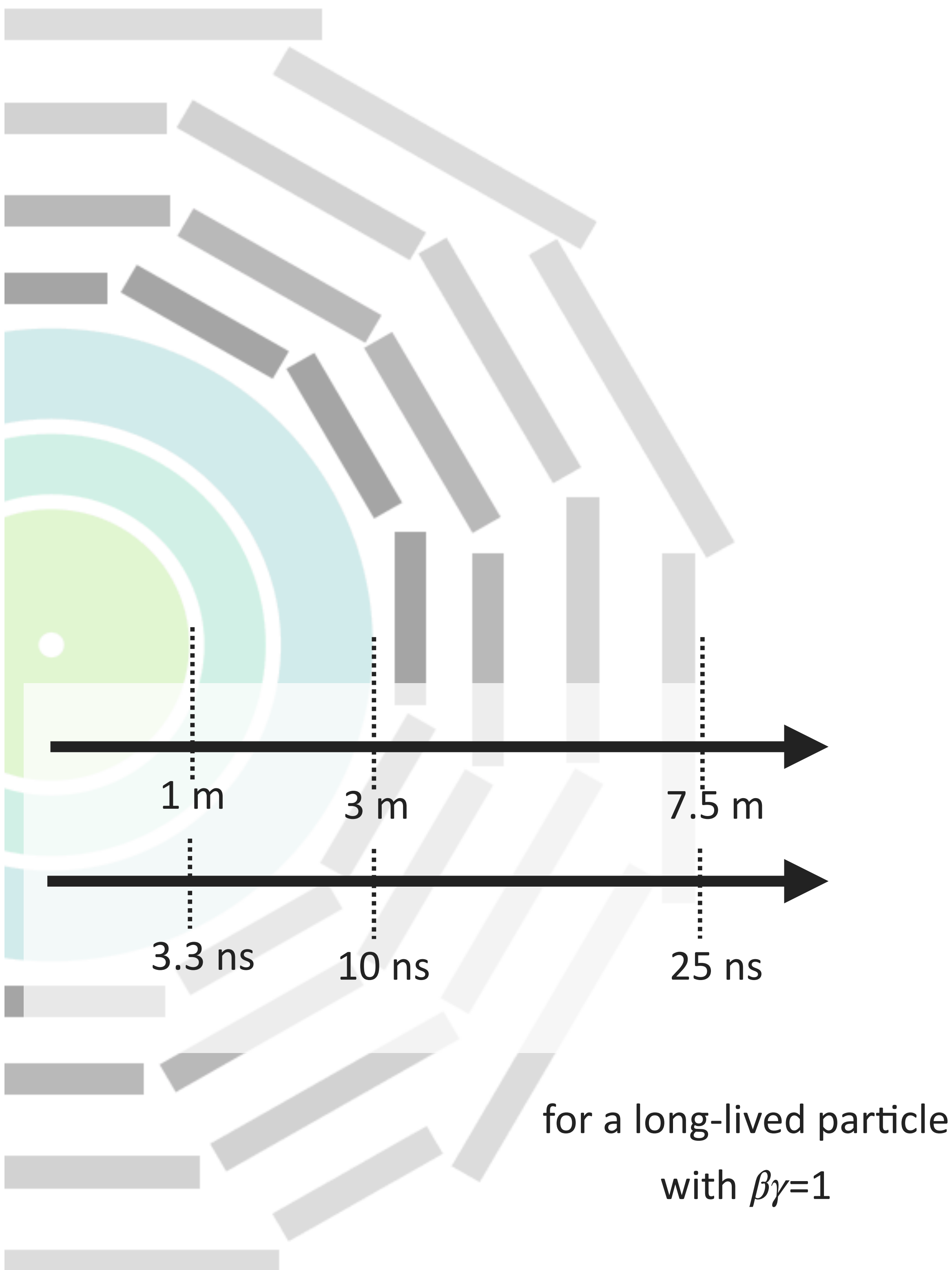
Well-motivated models could result in unconventional track signatures that may have evaded standard triggers & search strategies

The future is bright!

New interest in pushing boundaries of ATLAS/CMS capabilities to find overlooked physics


BACKUP SLIDES

Connecting detector and lifetime



Long-lived particle decay position is sampled from an exponential distribution

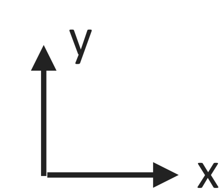
Mean distance travelled = $\beta\gamma c\tau$

$c\tau$ = distance metric

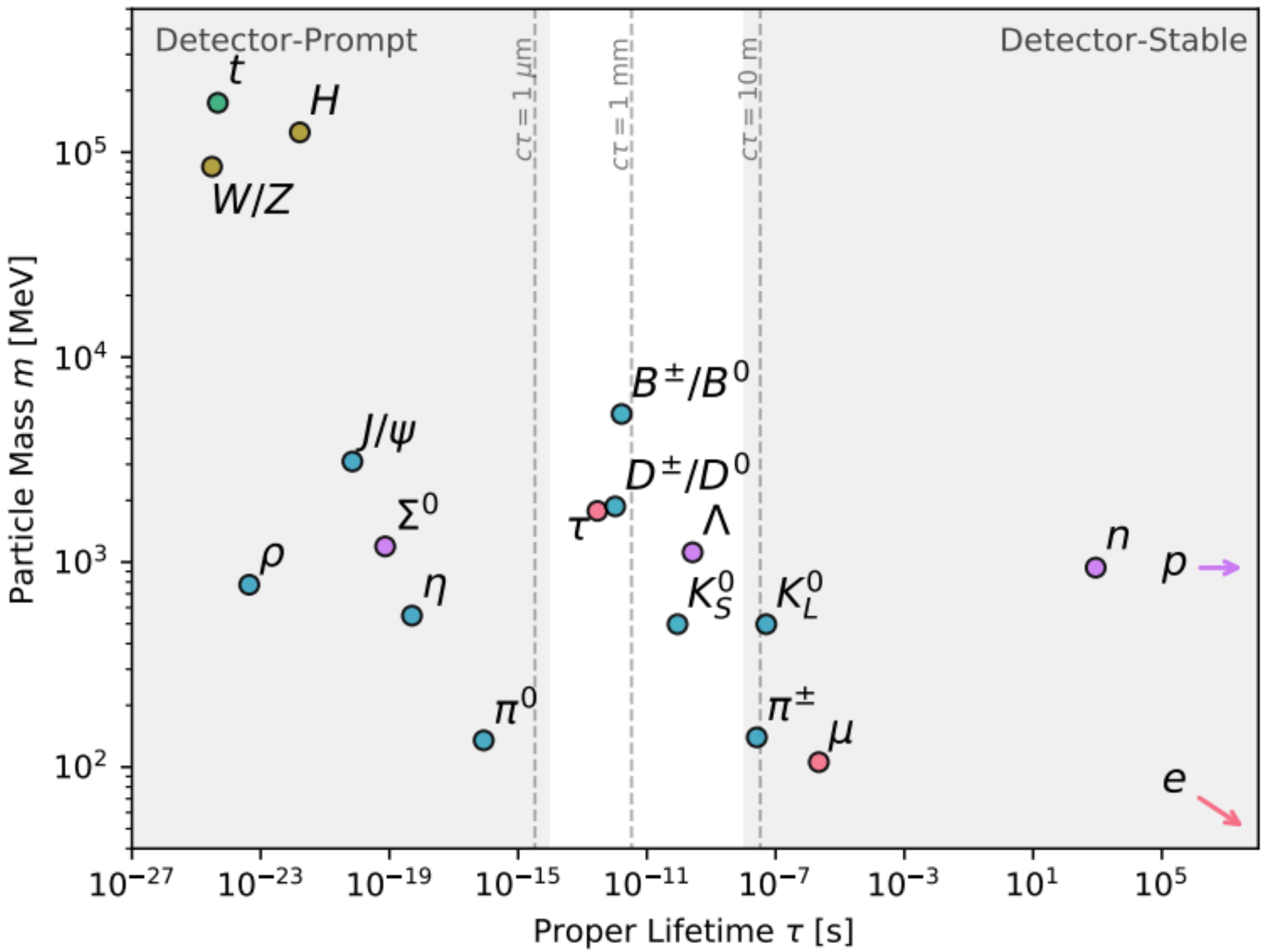
~ 30cm for τ = 1 nanosecond

Lorentz boost $\beta\gamma$ = p/M.

Ranges from ~ 0.8 or 0.9 for heavy particles to ~30 for light ones



SM Particle Lifetime



Inclusive displaced jets

[2012.01581](2012.01581)

Hadronic decay in Tracker

For hadronic LLP decays: story begins with flagship analysis (from 2020)

Analysis strategy: Select events with ≥1 displaced vertex reconstructed from tracks associated to a pair of jets

Dedicated trigger!

$H_T \geq 430$ GeV

≥ 2 displaced jets

~0.3% efficiency to ggF

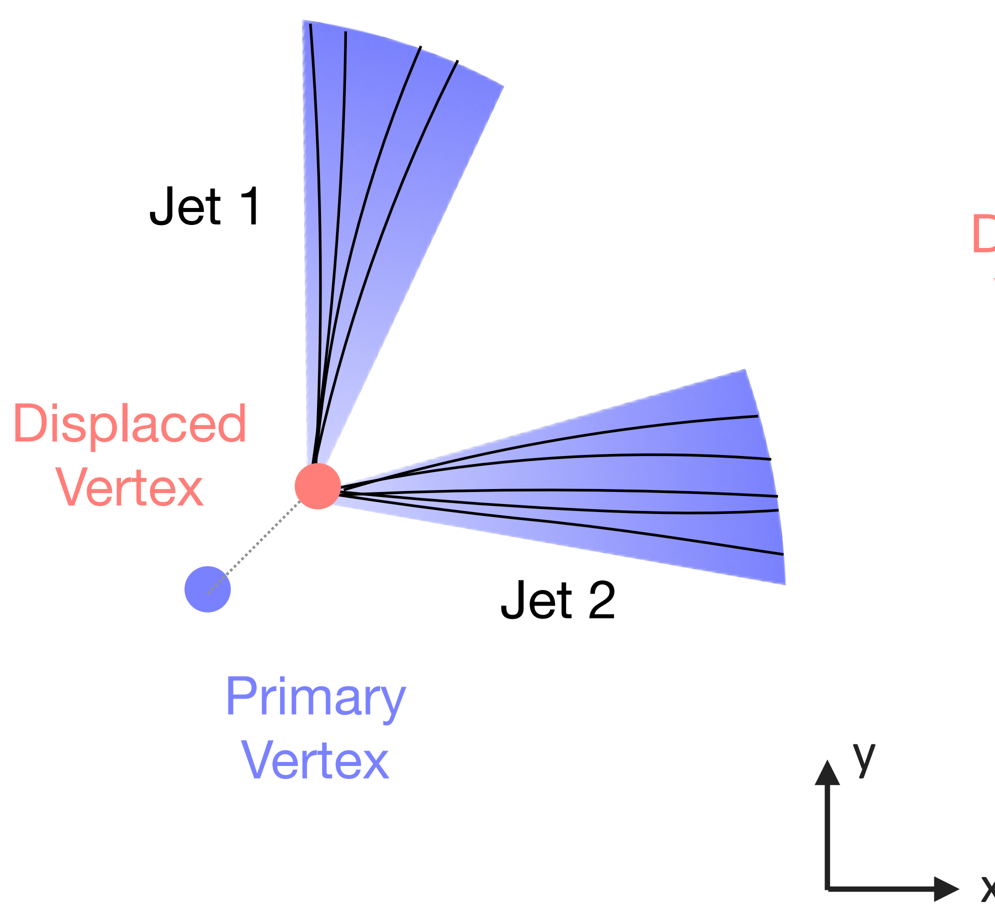
Results

0.75 ± 0.60 expected

1 observed

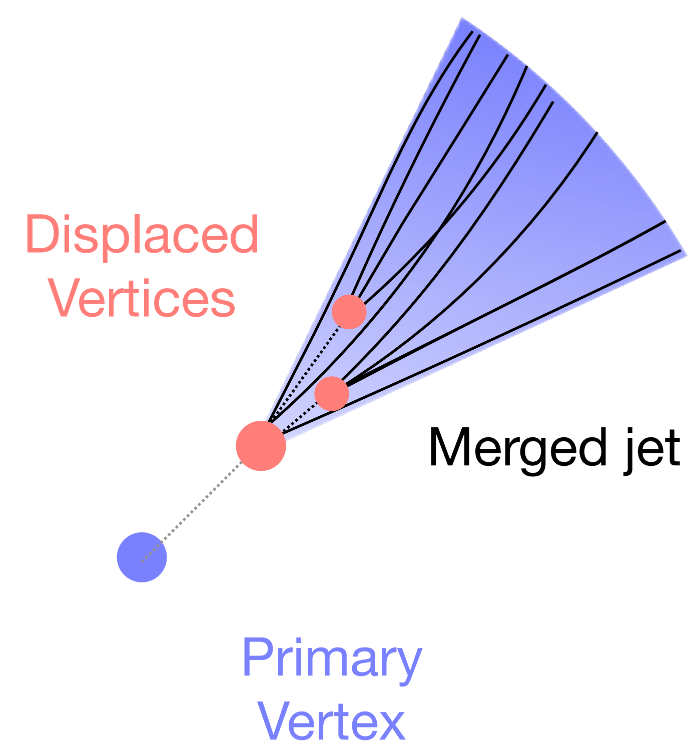
first CMS sensitivity to wide range of hadronic h→LLP decays

Target signature



Gap in coverage

$m_X < 20$ GeV, $X \rightarrow bb$



Z+displaced jets

New! EXO-20-003

Hadronic decay in Tracker

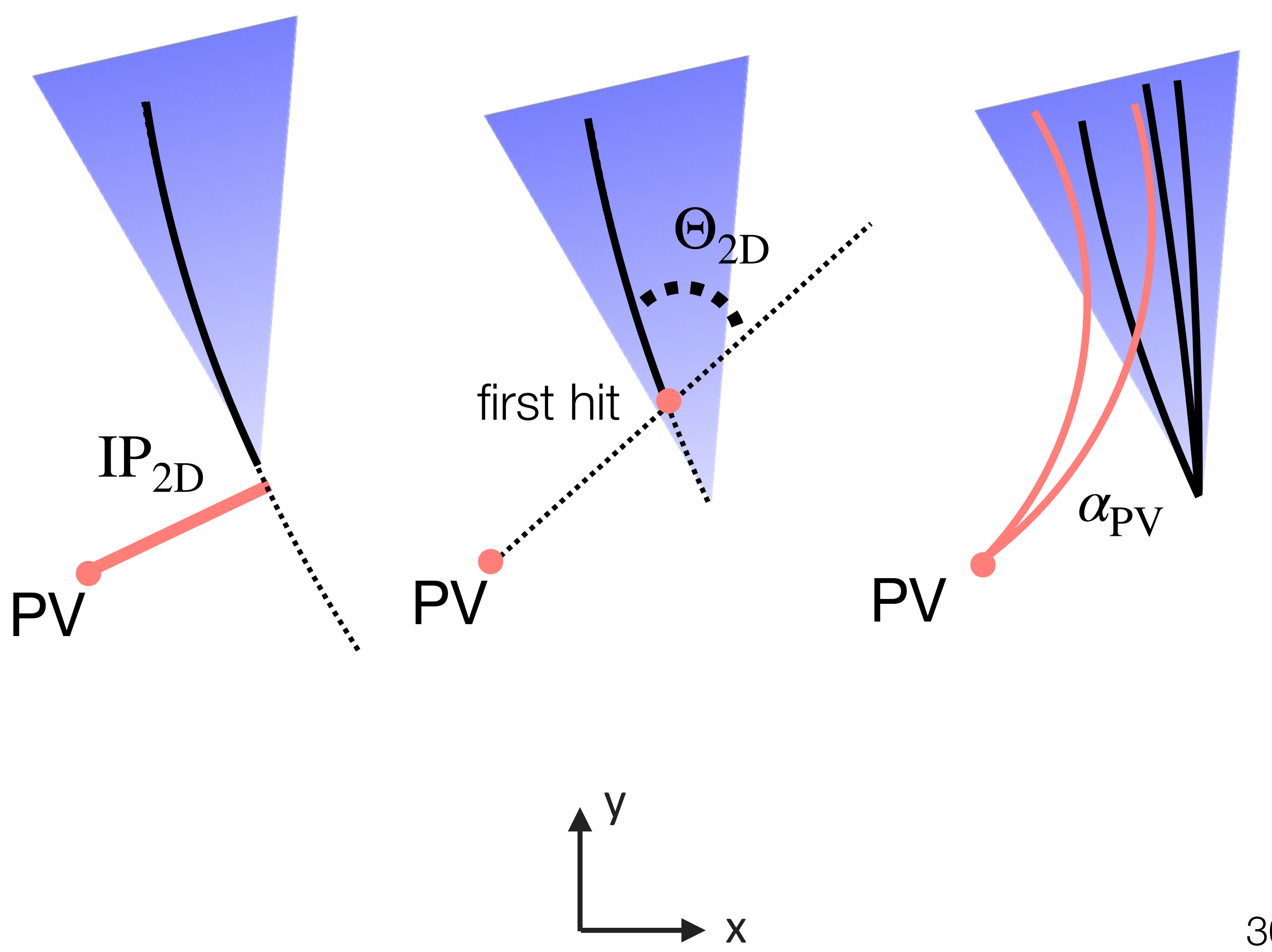
Analysis goal: follow up inclusive displaced jets
specifically targeting light LLP decays to b-jets

Trigger on Zh production
less boosted than inclusive analysis

Require ≥ two displaced jets
no displaced vertex required to retain efficiency to tertiary vertices

Results
3.5 ± 1.8 events expected
3 observed

Variables used to tag displaced jets
based on EXO-16-003

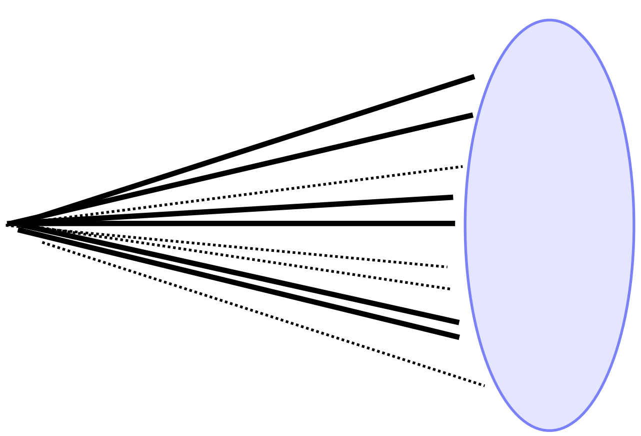


Dark QCD phenomenology

Easier if we just turn one knob at a time!

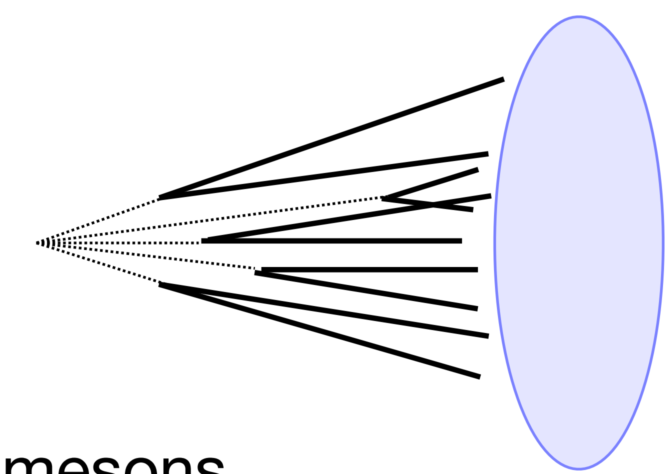
1. fraction of dark matter

Semi-visible jets



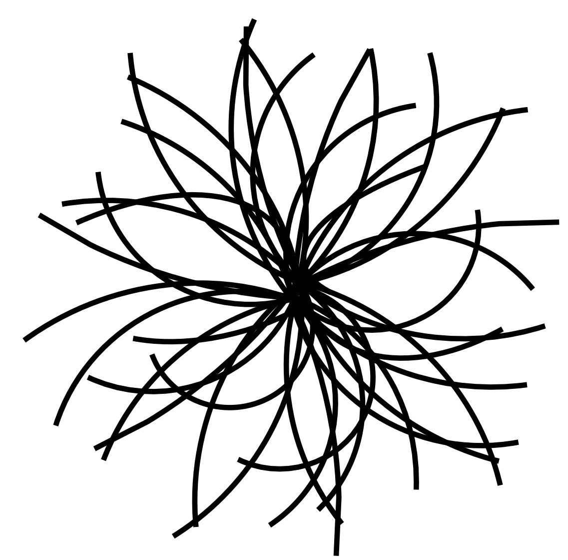
2. dark meson lifetime

Emerging Jets



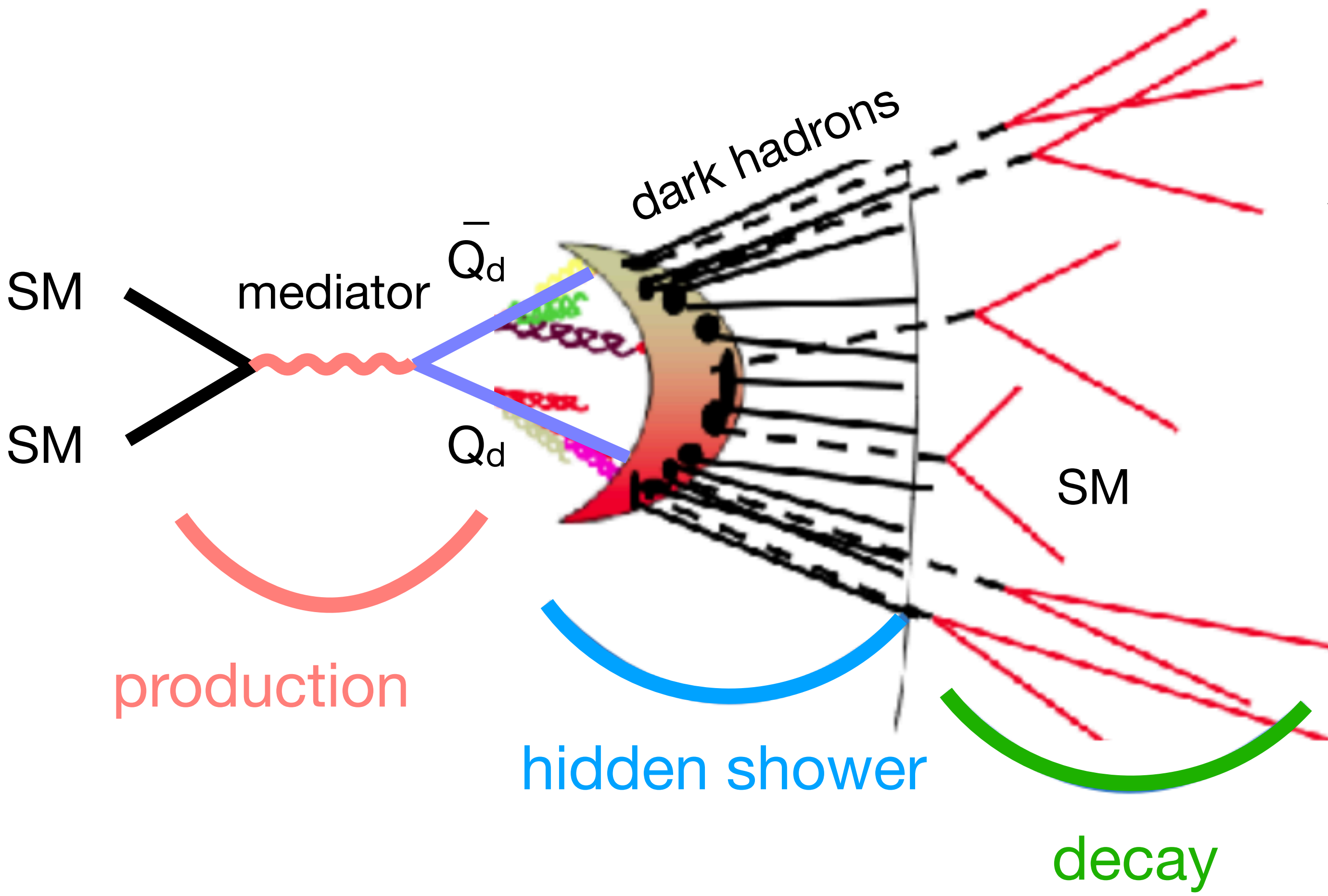
3. shower shape

Soft Unclustered
Energy Patterns



dark mesons
SM particles

SUEP phase space



Large t'Hooft coupling

$\lambda = \alpha^2_{dark} \cdot n_{colors}$

Wide angle, high momentum radiation

$M_{mediator} > M_{dark\ hadrons}$

High multiplicity final state

Dark hadron momenta parameterized by Maxwell Boltzman with temperature, T

Focus on mediator masses O(100) GeV and up
And dark hadron masses ~ 1 GeV