Title: Dark Matter scattering in dielectrics

Speakers: Simon Knapen

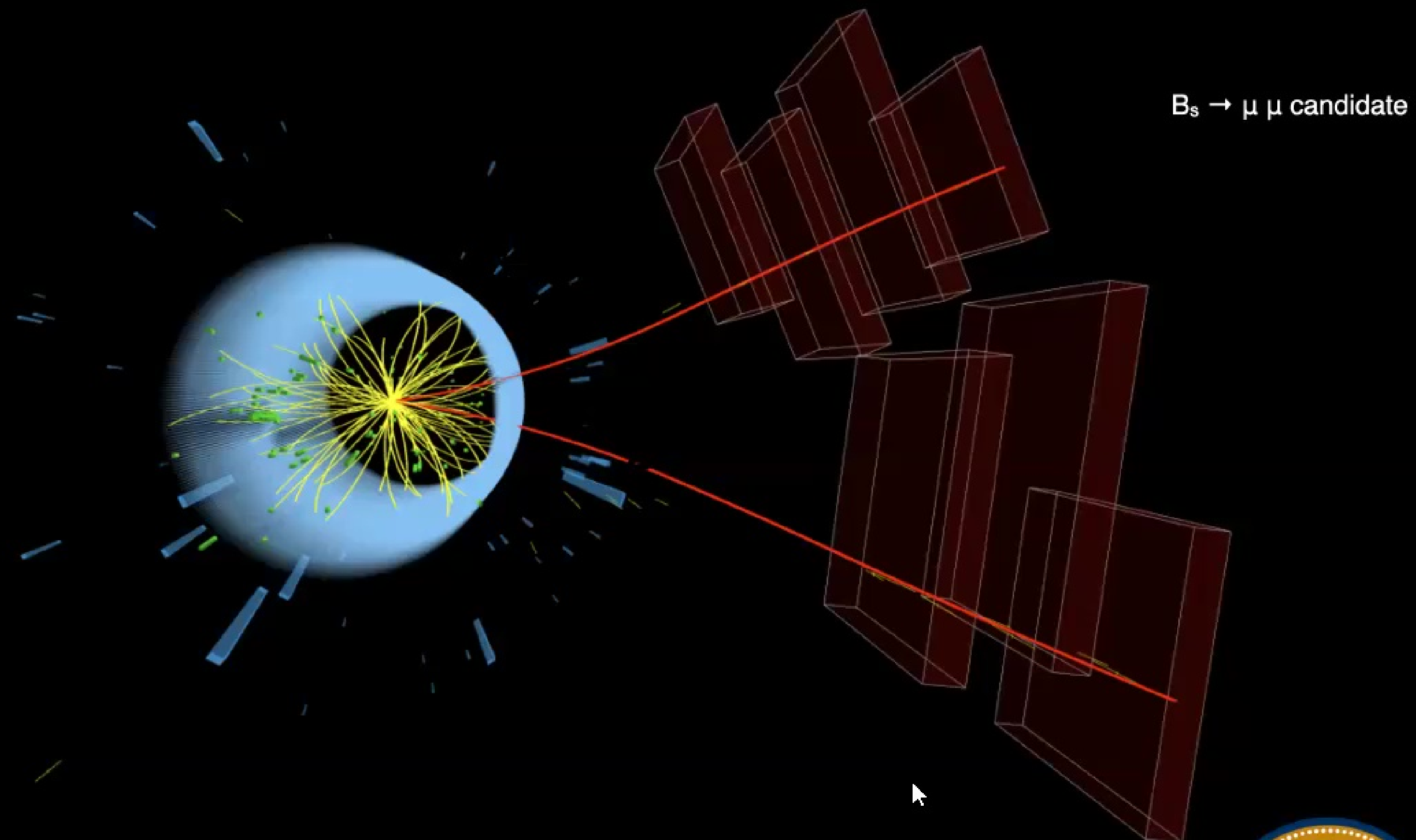
Series: Particle Physics

Date: September 14, 2021 - 1:00 PM

URL: https://pirsa.org/21090014

Abstract: I will discuss a set of calculations of dark matter interactions with low threshold semi-conductor detectors such as SENSEI and superCDMS. As a warm-up, I'll show how to rephrase traditional DM-electron scattering calculations in terms of the energy loss function of the material. We will then apply this framework to compute the rate for the Migdal effect in semi-conductor targets. This is needed because the traditional calculations of the Migdal effect do not apply in low threshold semi-conductor detectors, as the delocalized nature of the valence electrons is not taken into account.

Soft Signals at the high luminosity LHC



Simon Knapen
LBNL & UC Berkeley

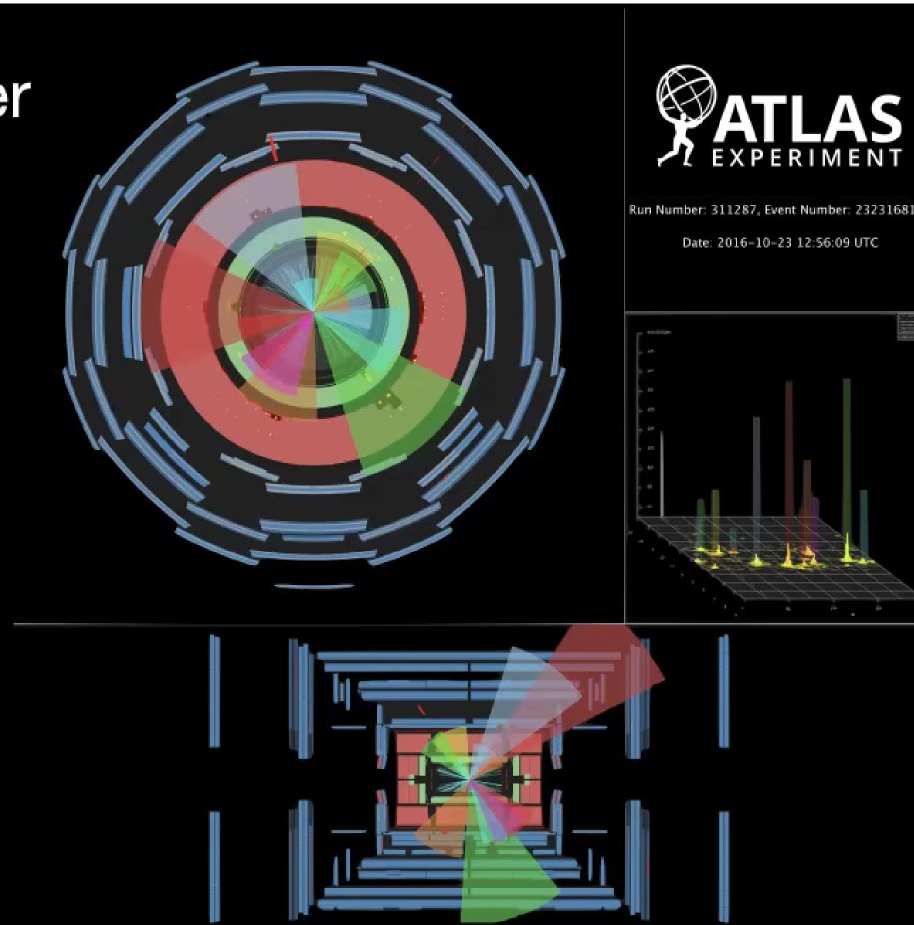
LHC on the energy frontier

Large data set:

150 fb^{-1} recorded

↓

7 x 10^6 Higgs bosons produced



N_{jets} = 13
ATLAS arXiv:1708.02794

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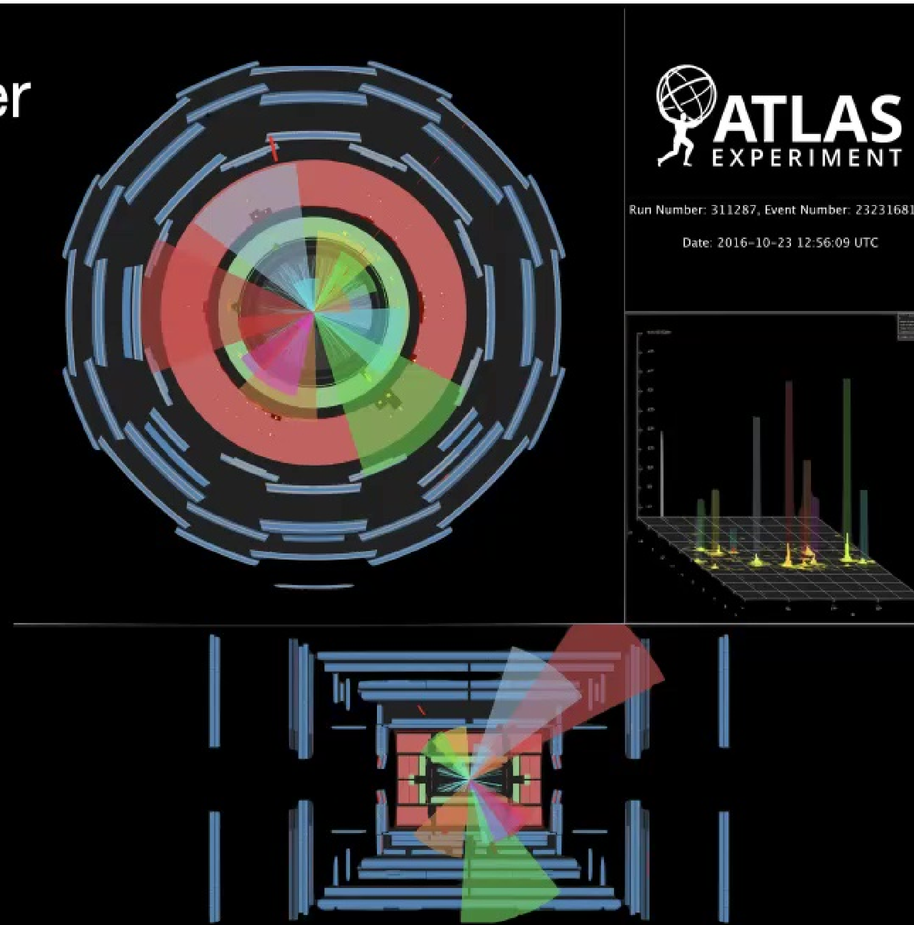


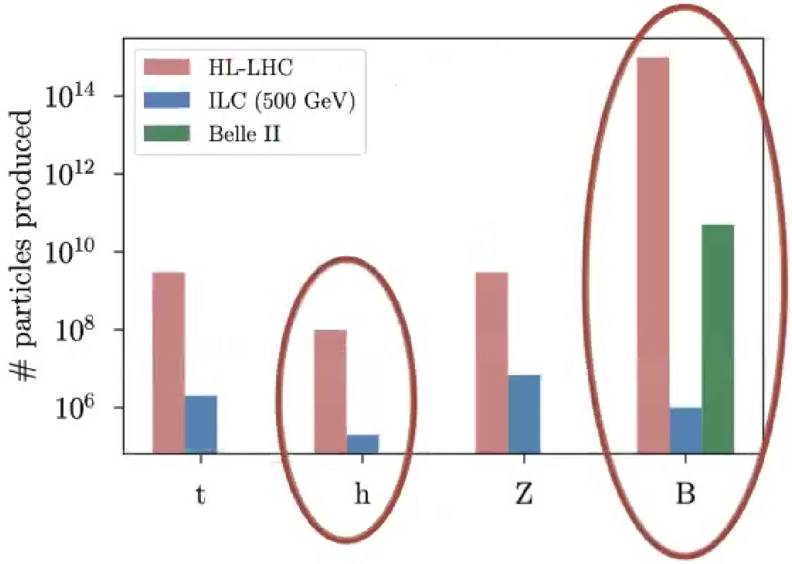
Analysis strategies *extremely sophisticated*

This example:
31 signal regions
+ corresponding control regions

$N_{jets} = 13$
ATLAS arXiv:1708.02794

LHC on the intensity frontier

Precision measurements often challenging, but huge particle yields



LHC on the intensity frontier

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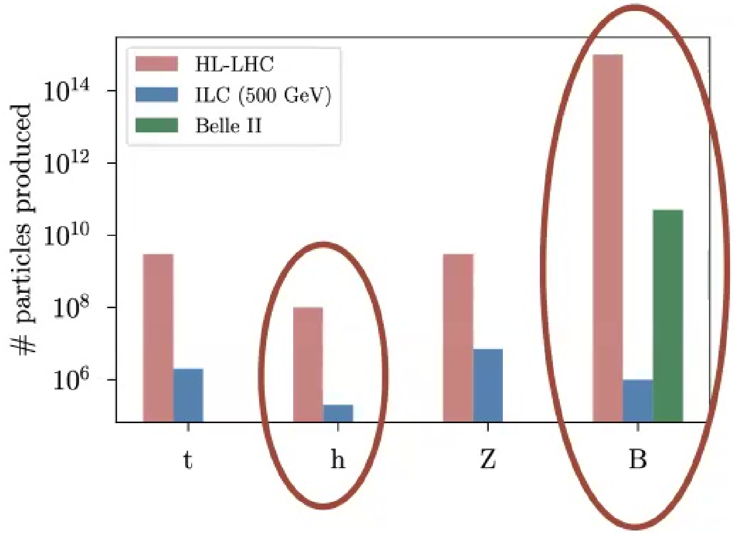


Yield for exotic decay modes:

$$\# = \text{Luminosity} \times \sigma_{B\bar{B}} \times \frac{\Gamma_{\text{exotic}}}{\Gamma_B}$$

~ 0.5 mbn

~ 0.4 meV

Sensitive to tiny couplings!

Complimentary sensitivity for signals with

- Low rates
- Relatively low backgrounds (online + offline)

New directions / priorities for the LHC

Precision measurements	Hadronic final states	Soft final states
↓	↓	↓
Precision Calculations	Machine learning	Trigger strategies Data scouting Special runs (e.g. Pb-Pb)

New directions / priorities for the LHC

The case for more theory involvement:

- Online selection increasingly sophisticated
- Resources are limited (bandwidth and people)

Theory priors
(Dark matter, naturalness, minimality, …)

Complementarity
(LHCb, Belle II, NA62, …)

Long-lived particles

Soft final states

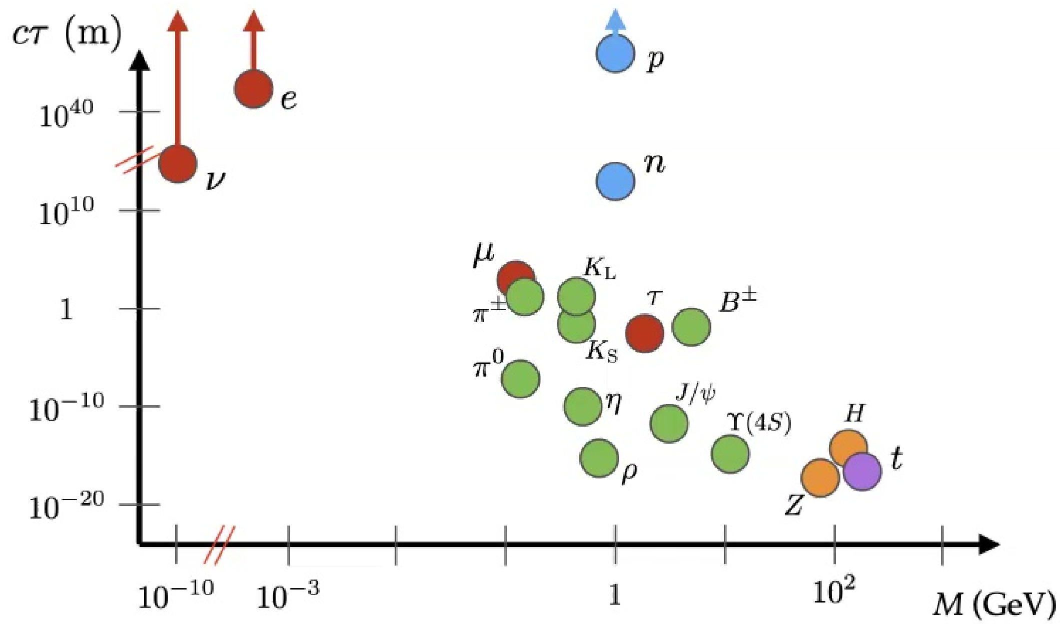
Trigger strategies
Data scouting
Special runs (e.g. Pb-Pb)

Long Lived particles

Why start with long-lived particles?

Pragmatic reason: Displaced decay gives new handle to reject backgrounds

Theory reason: Light particles tend to be long-lived

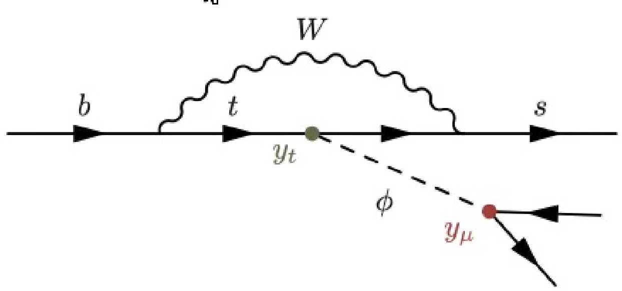


Plot by Brian Shuve

Another simple example

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 $m_\phi < m_B - m_K$)

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

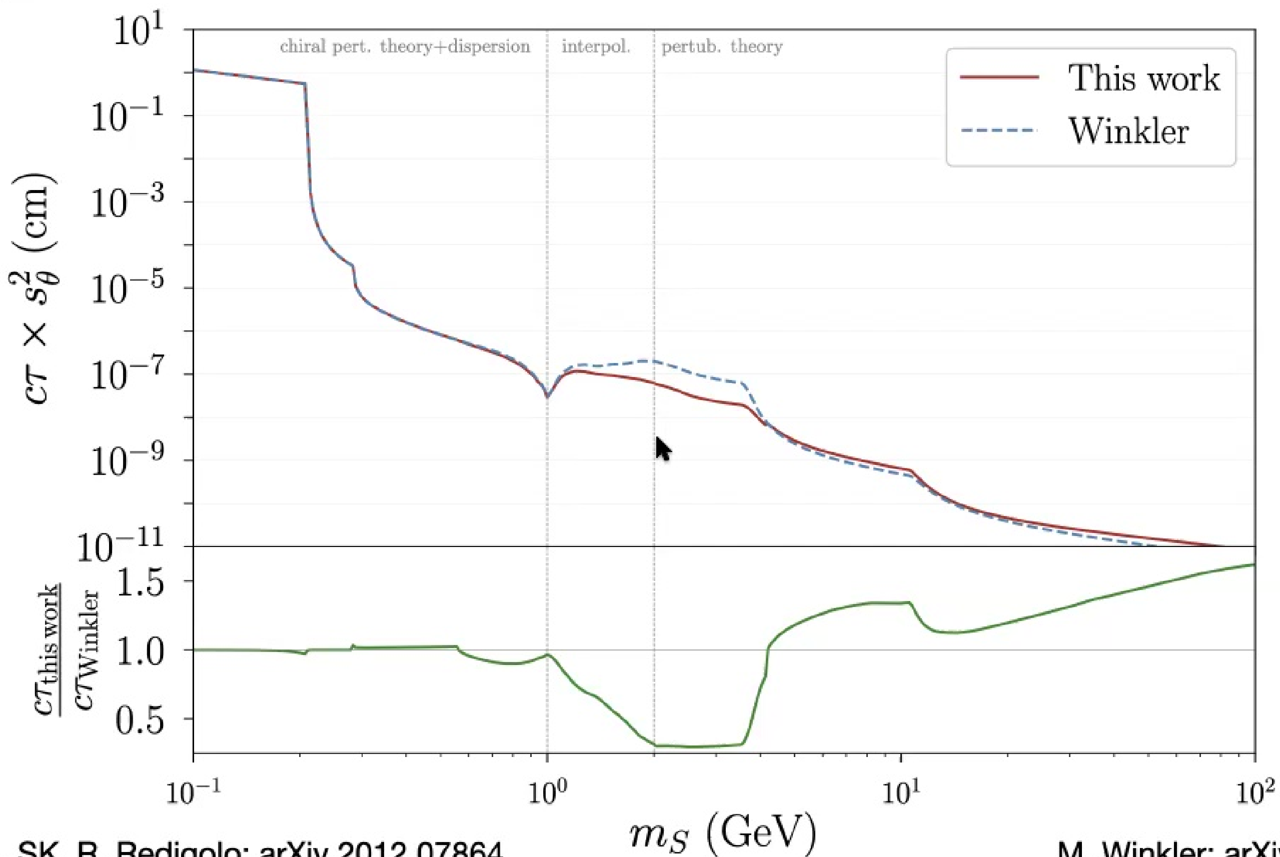
R. S. Willey and H. L. Yu (1982)
R. Chivukula and A. V. Manohar (1988)
B. Grinstein, L. J. Hall, and L. Randal (1988)
B. Batell, M. Pospelov, A. Ritz (0911.4938)
...

Another simple example

Scalar singlet extension of Higgs sector: $\mu\,\phi H^\dagger H$

(Most minimal extension of the Standard Model)

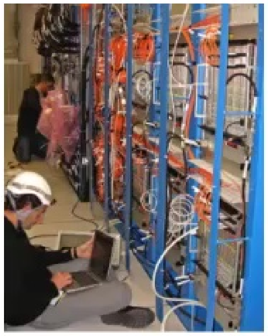
Decay:



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

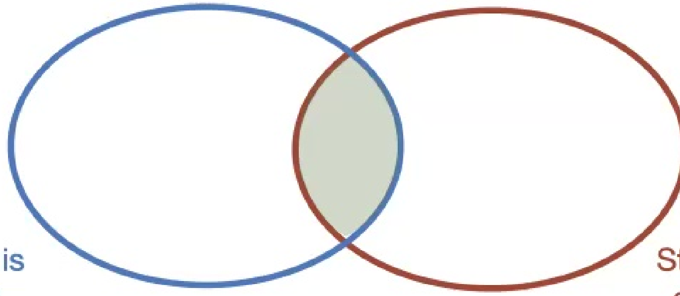
M. Winkler: arXiv 1809.01876

Things to do with the phase II upgrade



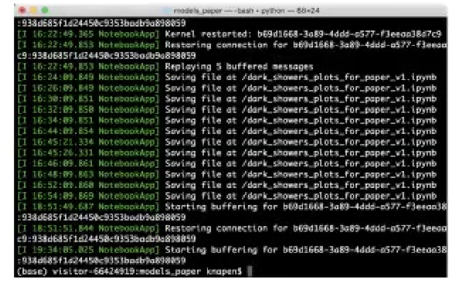
Experimental physics

Stuff that is feasible

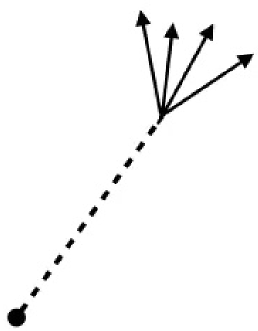


Stuff that we should try to do

Stuff that is desirable



Theoretical physics



Displaced vertex triggers

(Higgs & B decays)

Data scouting methods

(ALPs)

Things to do with the phase II upgrade

Experimental physics

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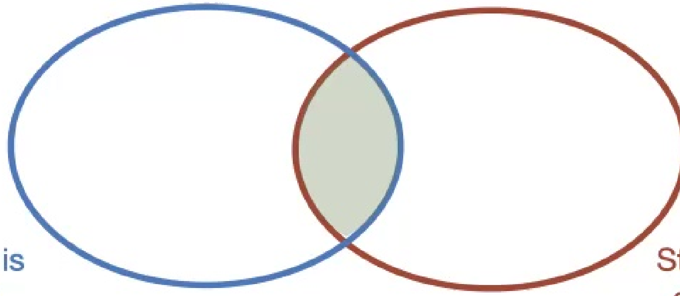

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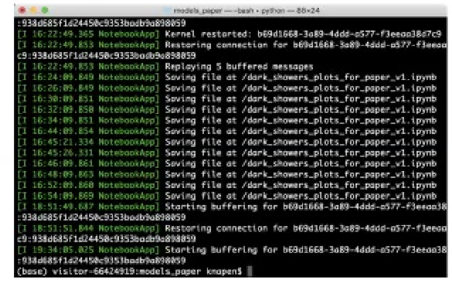

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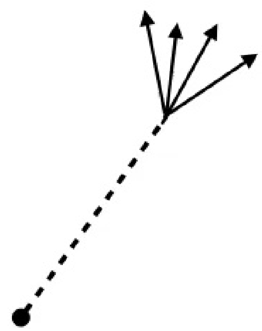


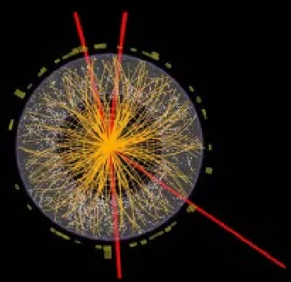
Displaced vertex triggers

(Higgs & B decays)

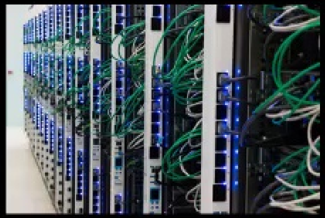
Data scouting methods

(ALPs)

Trigger basics



Level 1 (L1)



High level (HLT)

40 MHz

100 kHz

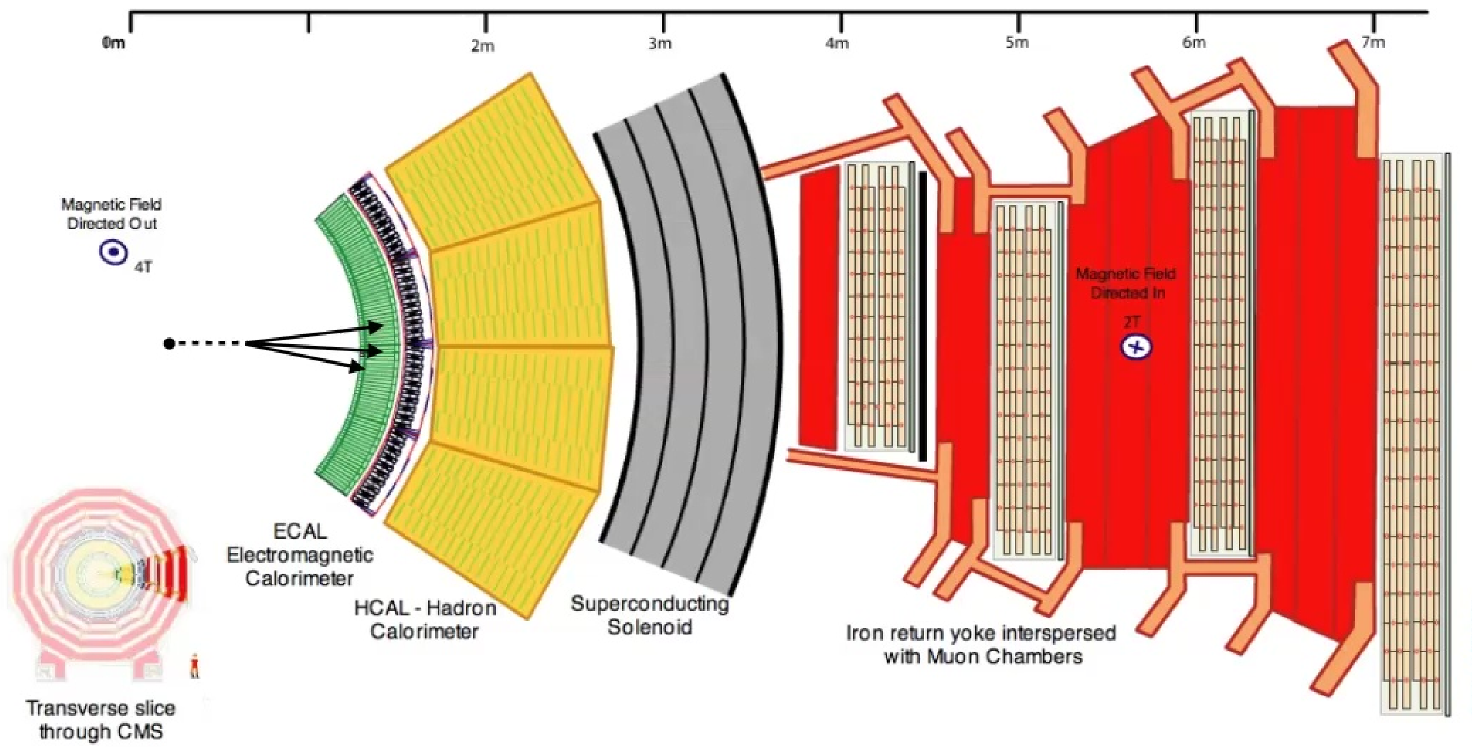
1 kHz

Only 0.0025 % of all collisions get recorded

→ Triggers are critical to the experimental programs at ATLAS, CMS and LHCb!

Currently only tracking at HLT step

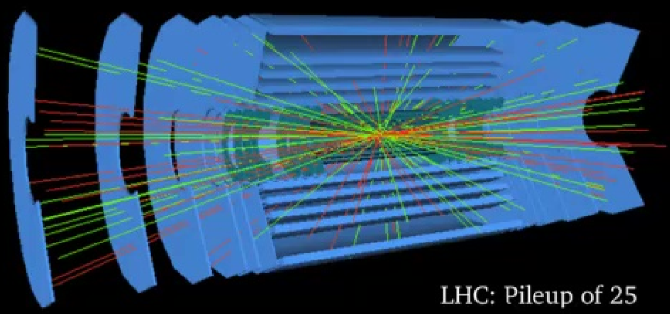
Detector layout as seen by L1 trigger

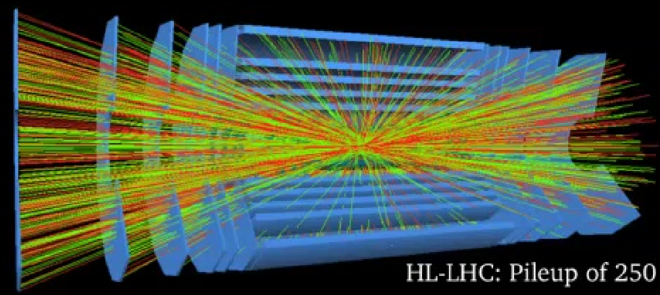


Displaced decay looks prompt to the L1 trigger, and is unlikely to be recorded

Triggers at HL-LHC

~200 collisions per event in HL-LHC conditions





ATL-UPGRADE-PROC-2012-003

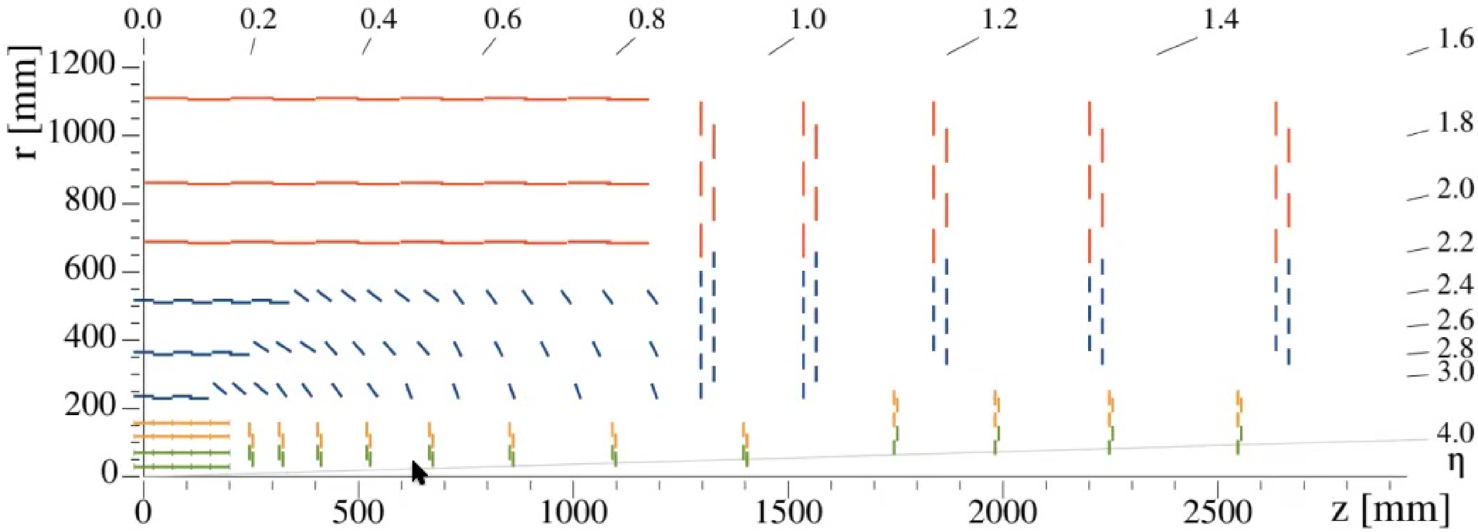
Major upgrades to the trigger being developed:

- More bandwidth
- More capabilities → tracking at L1 trigger!

What else can we do beyond just pile-up mitigation?

CMS Level 1 track trigger

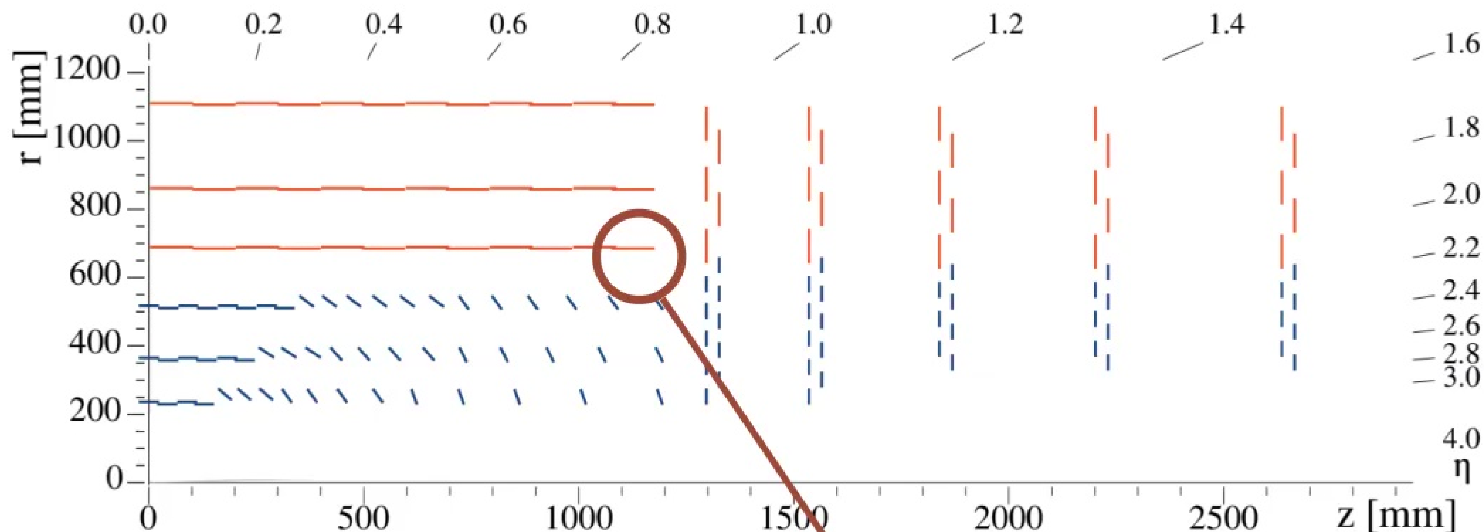
Phase II tracker layout



CMS-TDR-014

CMS Level 1 track trigger

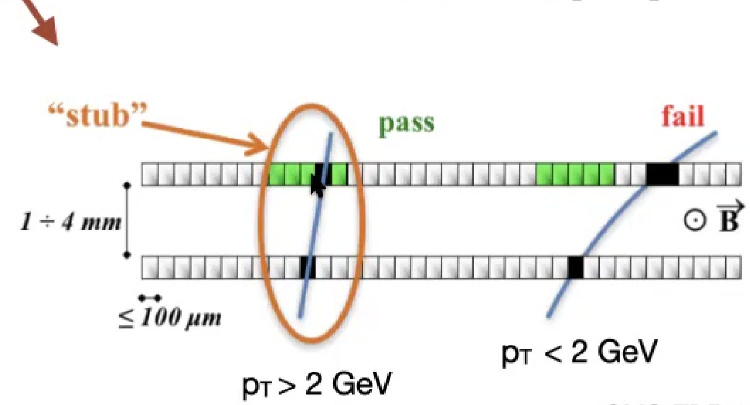
Phase II tracker layout



Each module independently measures the p_T of the stubs

↓

Only stubs with $p_T > 2$ GeV are used in track reconstruction



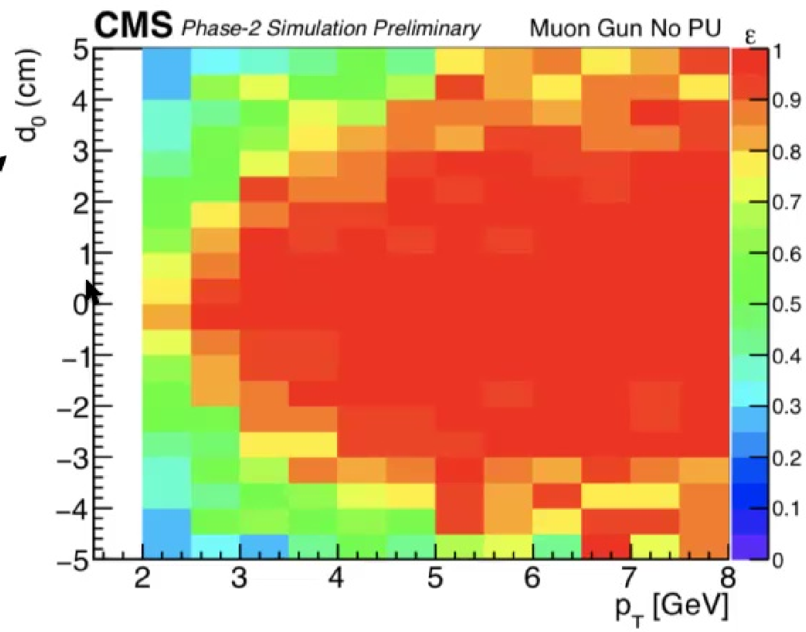
CMS-TDR-014

Displaced tracks

Key point: For moderate displacements, stubs are still reconstructed

In principle, track trigger could find displaced tracks

Impact parameter in the transverse plane



Y. Gershtein: arXiv 1705.04321
CMS PAS FTR-18-018

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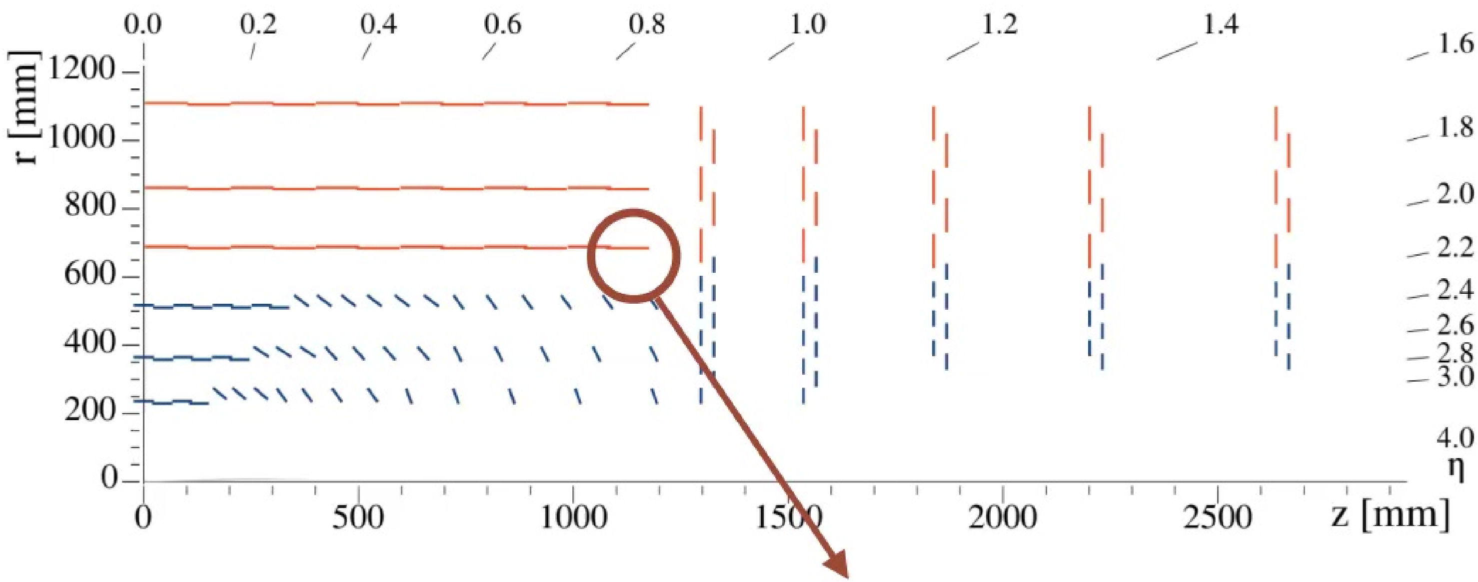

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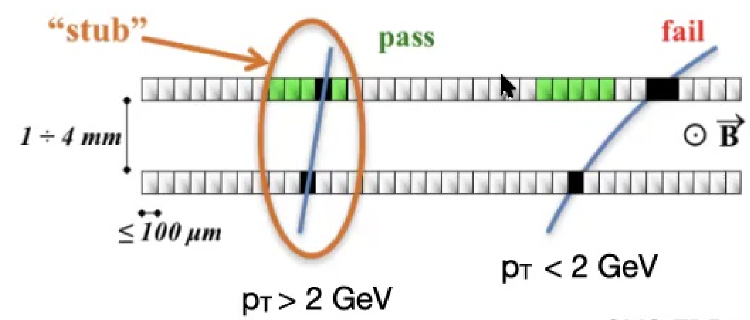

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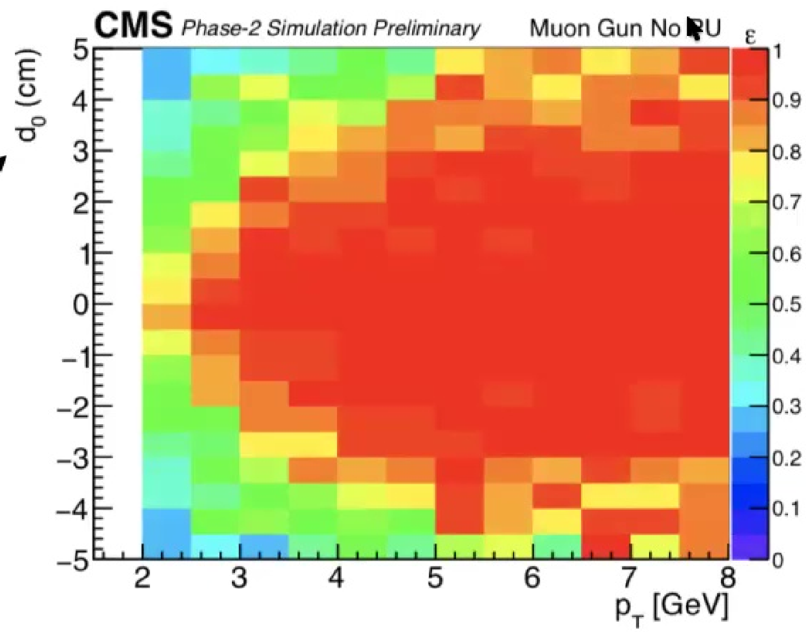

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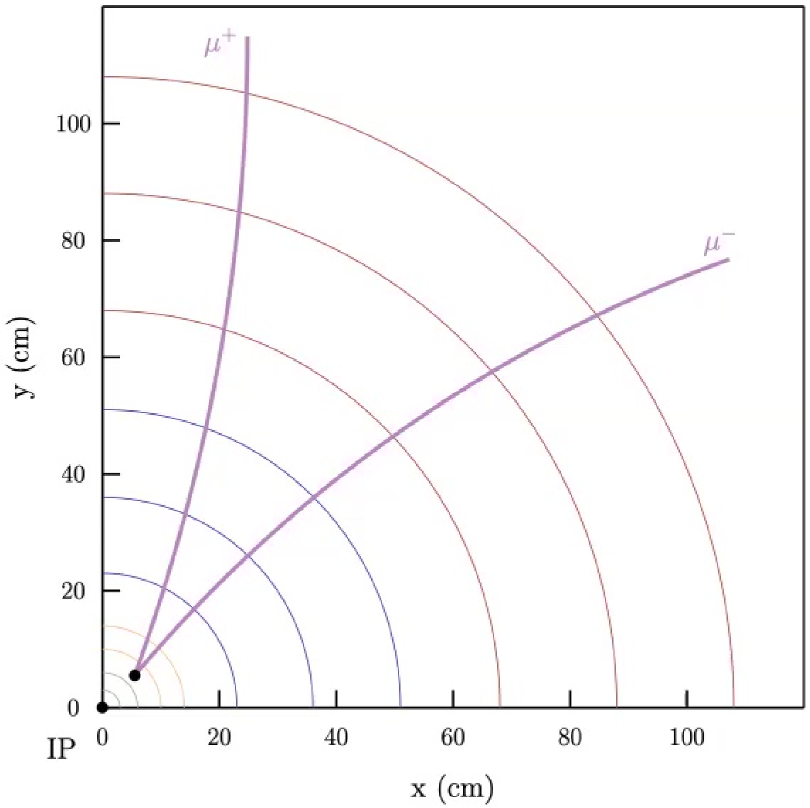
Toy detector simulation



Procedure:

1. Propagate track
   (including multiple scattering)
2. Find the stubs
   (smearing for resolution)
3. Fit a helix to the stubs
   (require at least 5 stubs)
4. Reconstruct a vertex

Y. Gershtein: arXiv 1705.04321
Y. Gershtein, SK: arXiv 1907.00007
Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864

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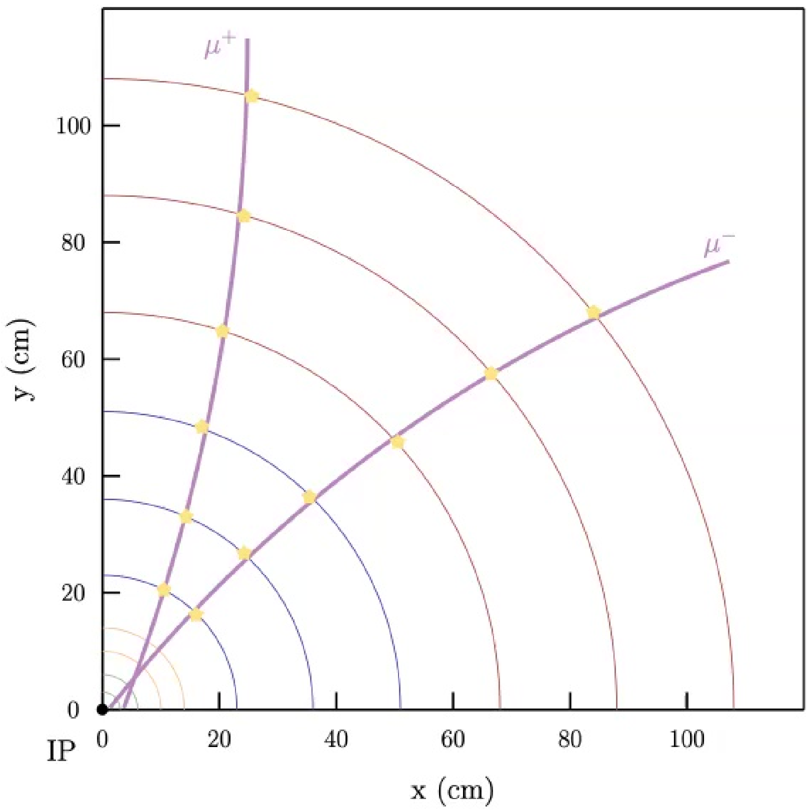

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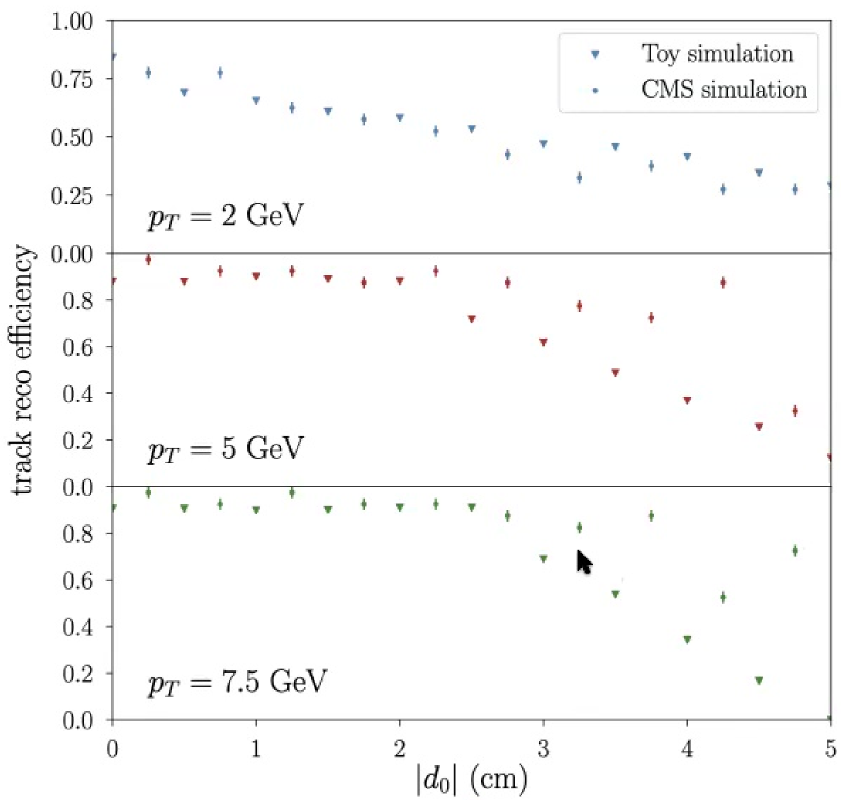

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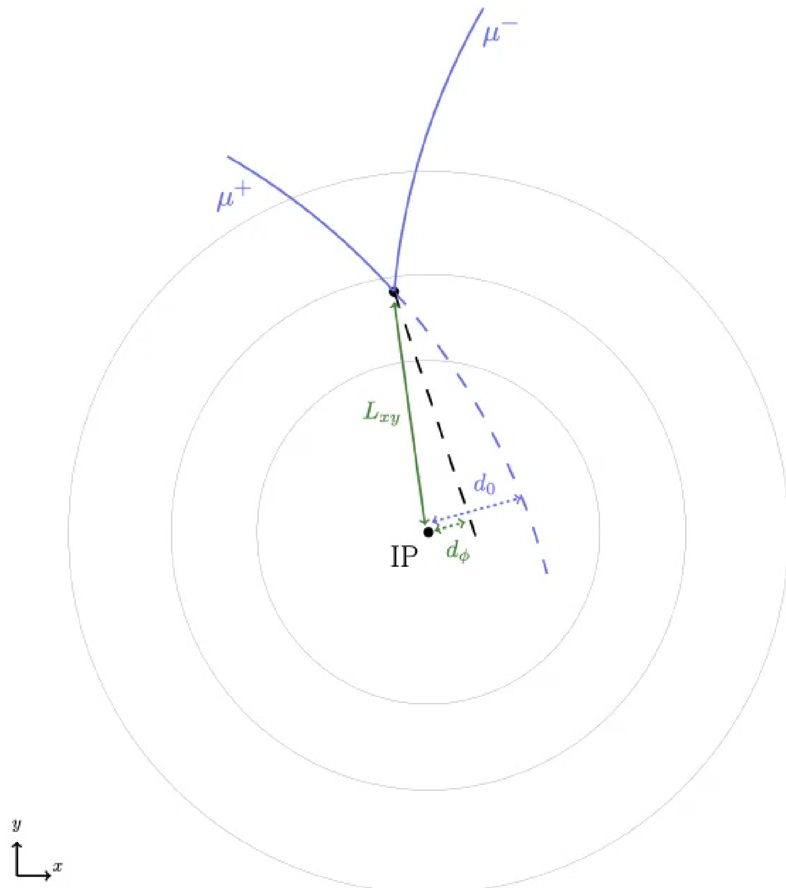
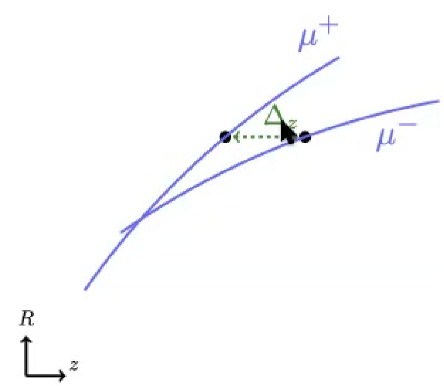
Some notation



Vertex is never perfect:
Δ_z measures vertex quality

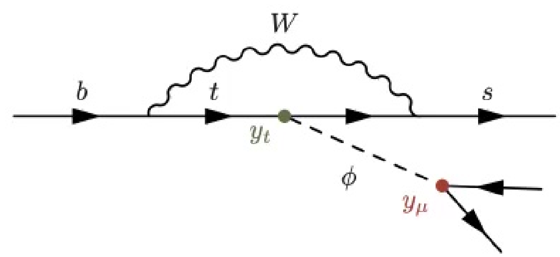


Y. Gershtein, SK: arXiv 1907.00007

Signal & Background

Signal: displaced dimuon resonance

$$B \to X_s \phi$$
$$\hookrightarrow \mu\mu$$



Backgrounds:

- Fake vertices → Vertex quality & muon matching
- Kaons $(K_S \to \pi^+\pi^-)$ → Muon matching
- B-mesons → Cut vertex radial distance (L_{xy}>1.5 cm)

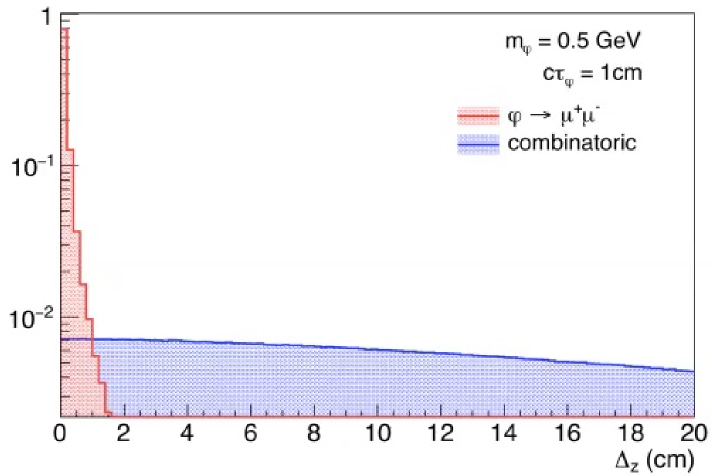
Goal: suppress background factor of 10^{-4} with minimal cuts on signal

Y. Gershtein, SK: arXiv 1907.00007

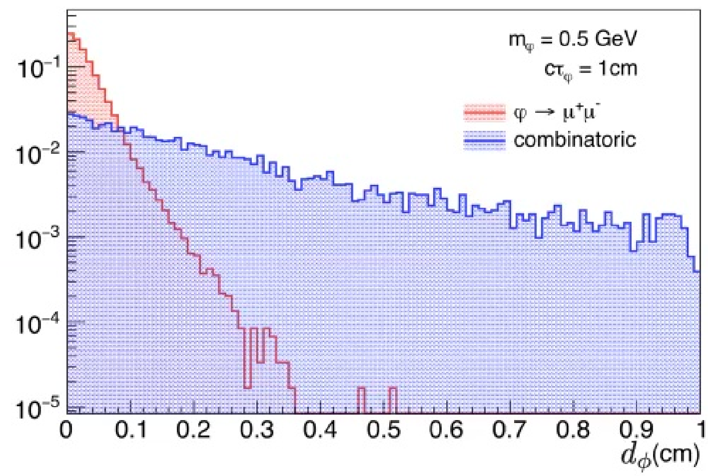
Fighting fakes

Assume 30 fake tracks per event → 225 fake “vertices” per event!

Distance between tracks in z-direction



Impact parameter of mother



$$\Delta_z < 1.0 \text{ cm}$$

↓

~ 10^{-2} suppression

$$d_\phi < 0.1 \,\text{cm}$$

↓

~ 10^{-2} suppression

Y. Gershtein, SK: arXiv 1907.00007

Background rates

Target: backgrounds ≲ 1kHz

Rates, *before* demanding matching with muon system:

minimum p_T selection	fakes (kHz)	K_S (kHz)
(3, 3) GeV	1000	800
(4, 4) GeV	600	240
(5, 3) GeV	840	200

Rate in ~ 1 kHz regime if the muon fake rate ≲ 5% per track
(see CMS-TDR-021)

Y. Gershtein, SK: arXiv 1907.00007

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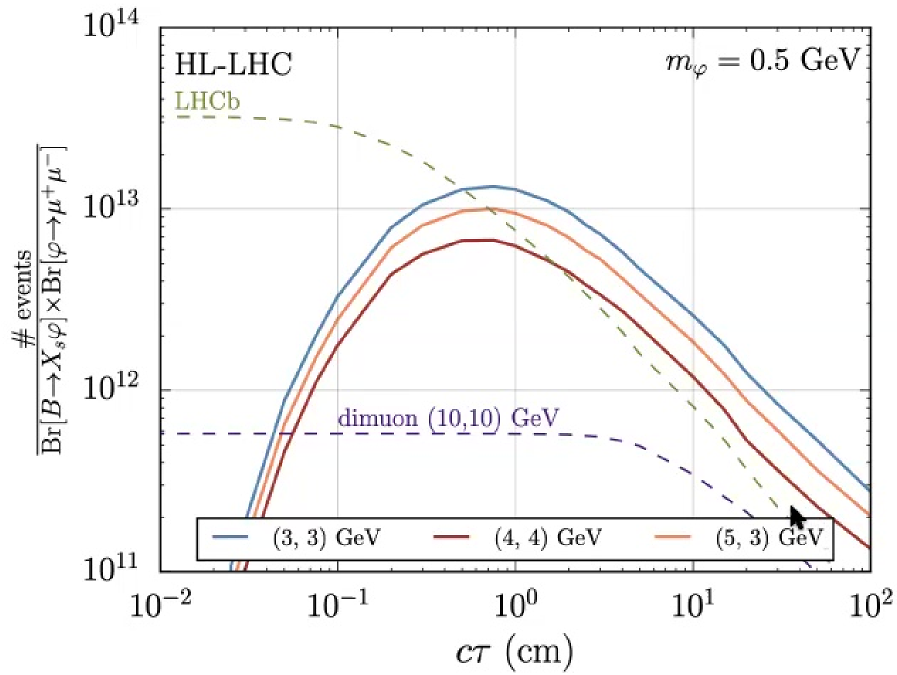
(see CMS-TDR-021)

L_{xy} > 1.5 cm and d_0 > 0.1 cm reduce true muons from B-meson decays < 1 kHz

Y. Gershtein, SK: arXiv 1907.00007

Trigger yield

Total yields for our (Level-1) trigger strategy, for different pT thresholds



Competitive with LHCb, much better than a (generous) normal dimuon trigger

Y. Gershtein, SK: arXiv 1907.00007

LHCb searches

Exclusive search strategy: reconstruct the whole decay chain

$B^{\pm} \to K^{\pm}\varphi \to K^{\pm}\mu^{+}\mu^{-}$ arXiv:1612.07818

$B^{0} \to K^{*0}\varphi \to K^{\pm}\pi^{\mp}\mu^{+}\mu^{-}$ arXiv:1508.04094

Reconstruct both vertices in the VELO

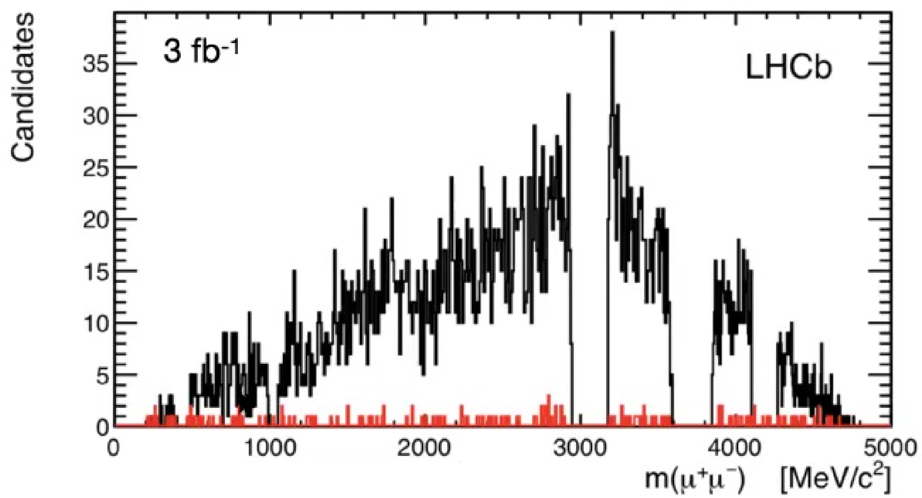
<u>3 lifetime bins:</u>

Prompt: $t < 1\,\mathrm{ps}$

Displaced: $1\,\mathrm{ps} < t < 10\,\mathrm{ps}$

Very displaced: $10\,\mathrm{ps} < t$

Low background, but fairly low signal efficiency



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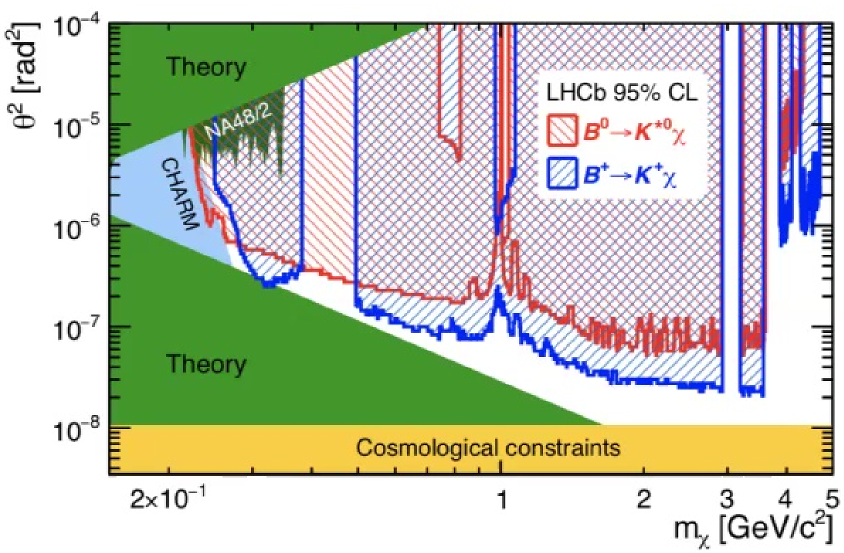


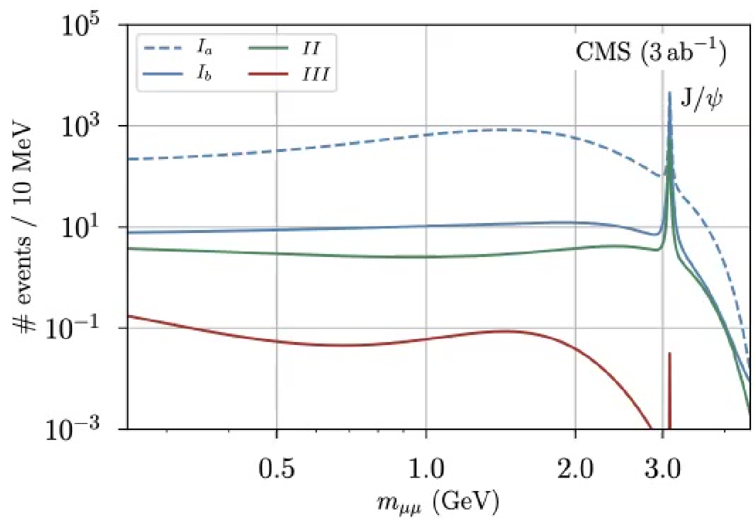
Low background, but fairly low signal efficiency

Offline analysis

Main background from B-meson decays

For example:

$$B^+ \to \mu^+ \nu_\mu D^0 X$$
$$\hookrightarrow \mu^- \bar{\nu}_\mu K^+$$



Can be reduced to O(1) levels with:

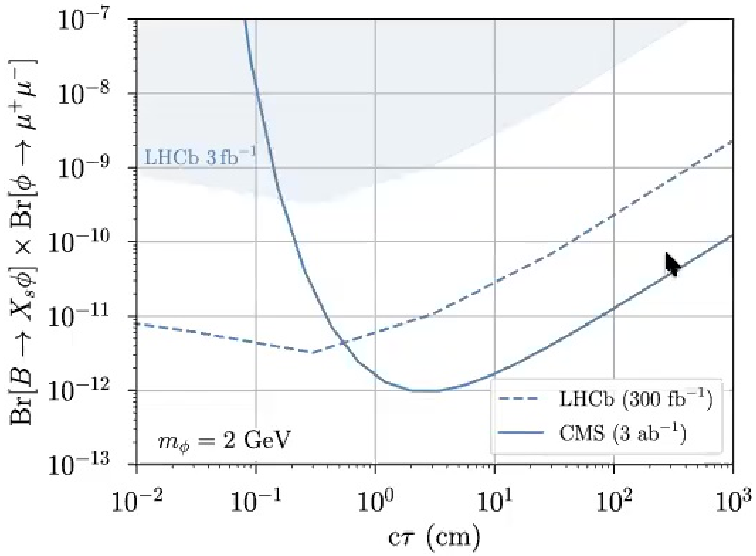
- Cuts on vertex displacement (> 7.5 cm)
- Isolation cuts
- Minimal pT cuts

J. Evans, A. Gandrakota, SK, H. Routray: arXiv 2008.06918

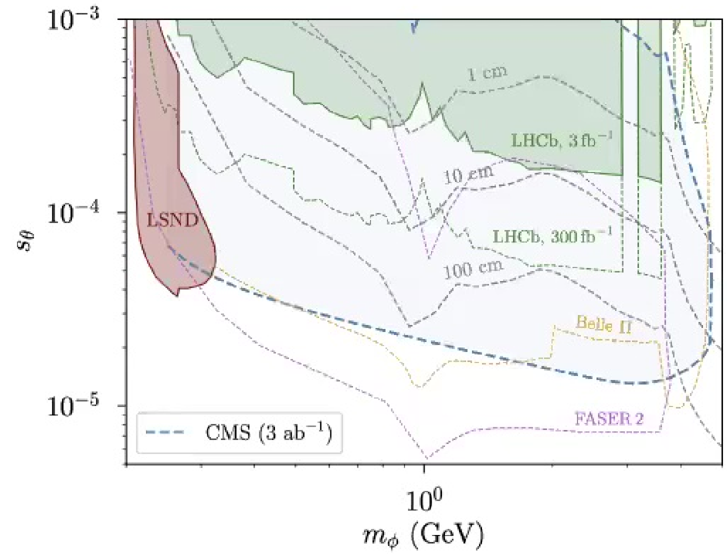
Projected sensitivity

Reach:

Model independent



Scalar mixing with Higgs



CMS reach is a bit optimistic, since “junk” backgrounds are not modeled

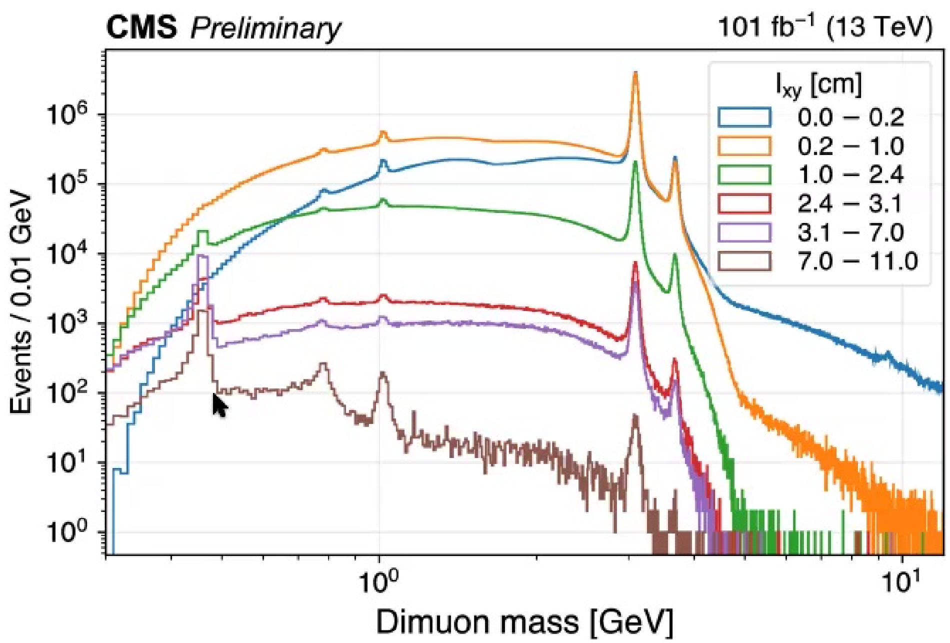
LHCb reach (optimistically) rescaled from current limits

J. Evans, A. Gandrakota, SK, H. Routray: arXiv 2008.06918

CMS scouting analysis

Scouting: record small fraction of the event

Allow to search of phenomena which would otherwise not pass the trigger thresholds



CMS EXO-20-014

VERY nice analysis!

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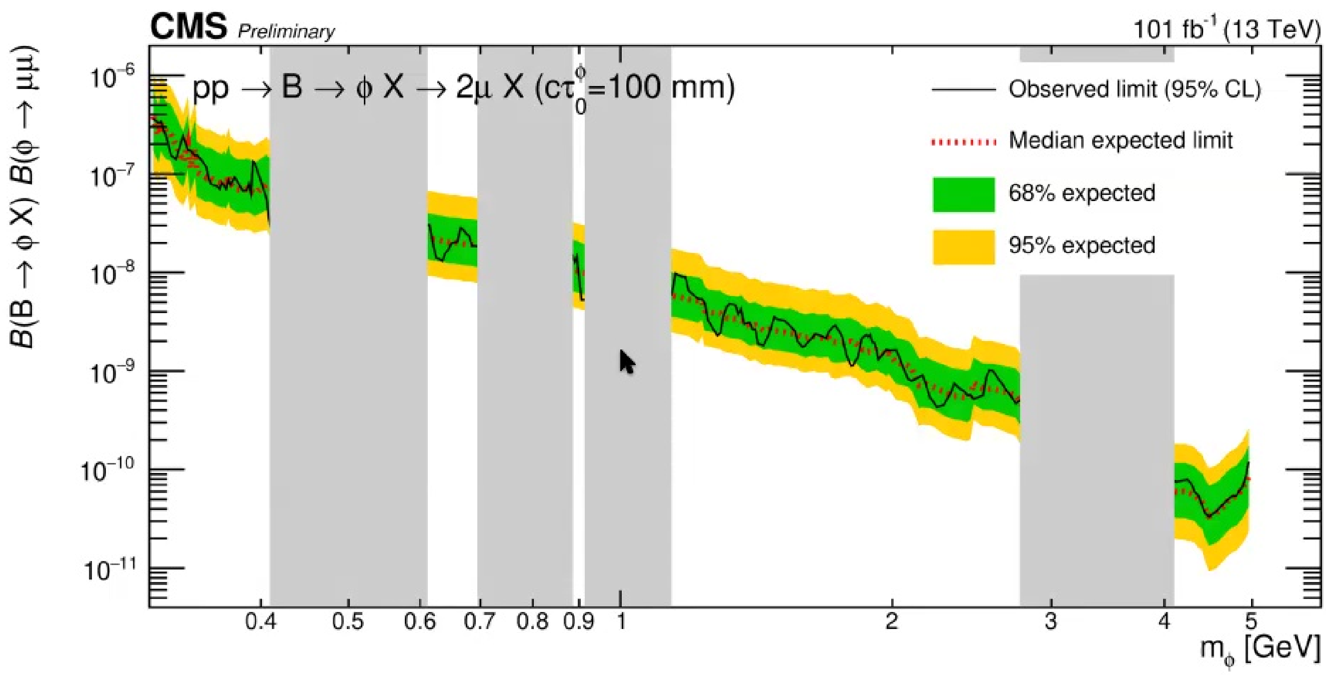
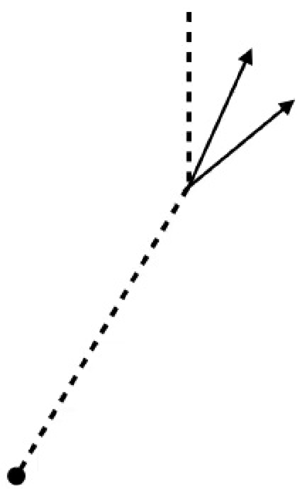


CMS EXO-20-014

VERY nice analysis!

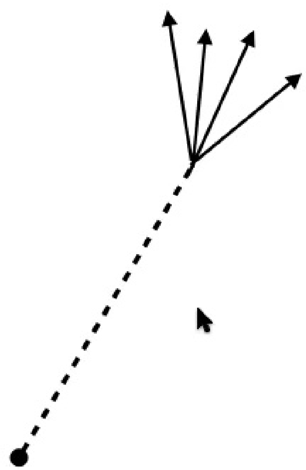
Other applications

DV + MET



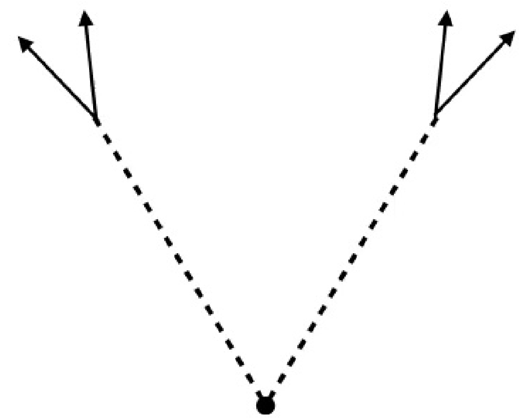
Heavy Neutral Leptons,
Inelastic Dark Matter

Multi-track DV



Axion-like particles
Exotic Higgs decays

Double DV

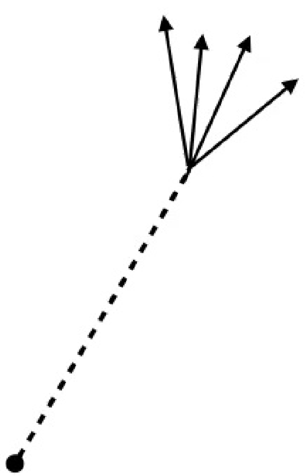


Dark Showers
Pair production of LLPs

Y. Gershtein, SK, D. Redigolo: in progress

Other applications of track trigger

Multi-track DV



Axion-like particles

Exotic Higgs decays

Selection

- 4 reconstructed tracks (pT > 2 GeV)
- Good quality vertex
- $L_{xy} > 3$ cm

Backgrounds

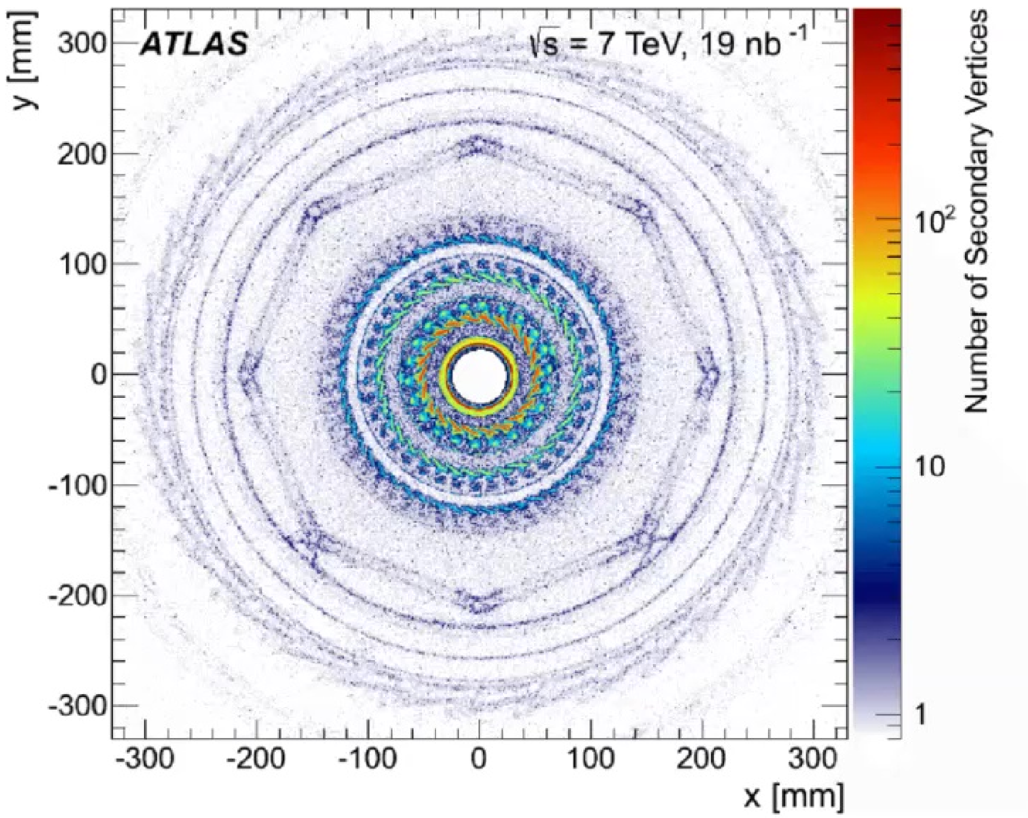
- Fake vertices → ≥ 4 tracks
- B-mesons → Vertex distance
- Material interactions → ??

Experimentally very challenging: must perform a preliminary study to verify that it is worth the effort

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

Material interactions

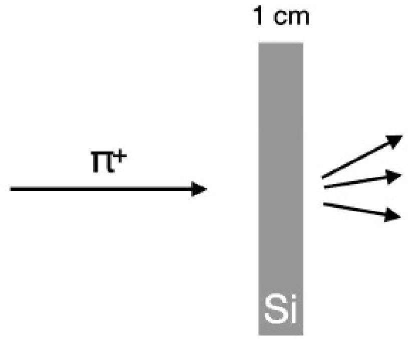
Standard Model particles create secondaries in detector material

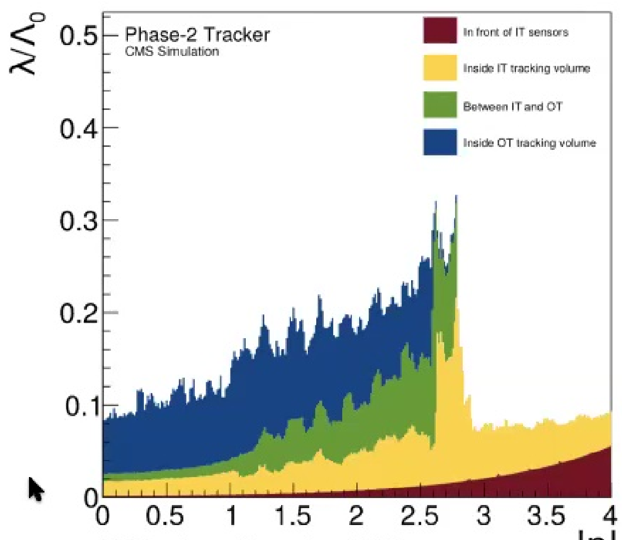


Must verify that this does not swamps the trigger bandwidth!

Interactions with detector material

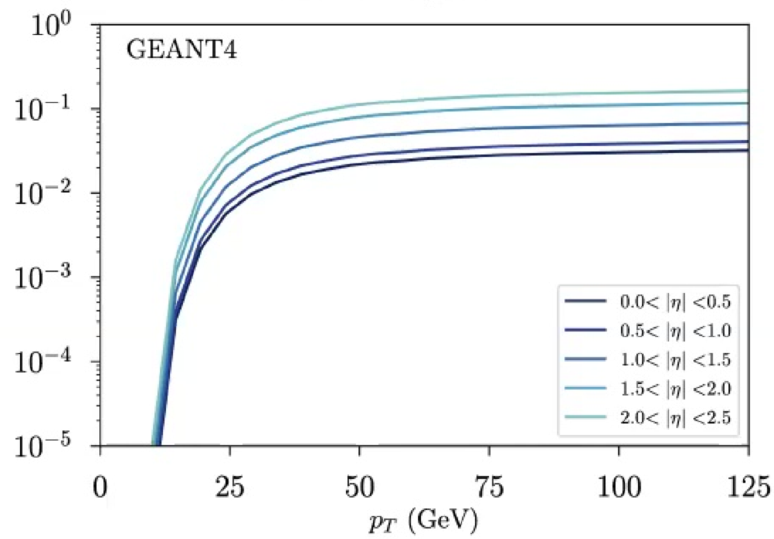
Pion gun in GEANT4





CMS phase II tracker TDR

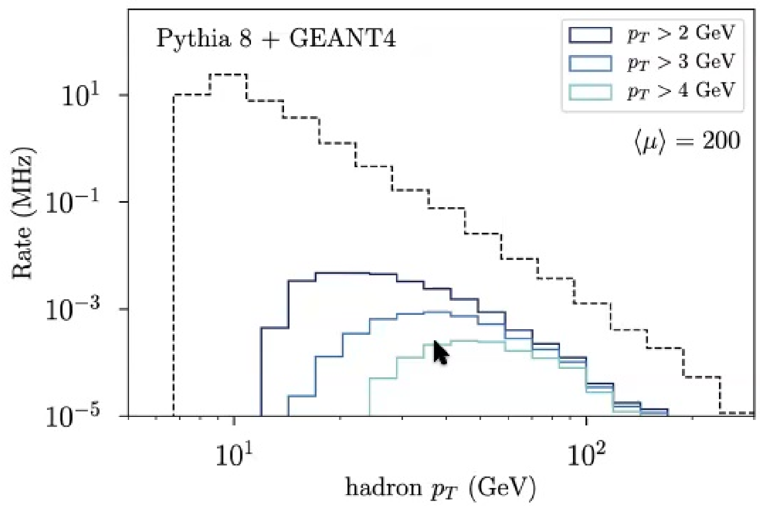
4 tracks with p_T > 2 GeV



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

Interactions with detector material

Fold in particle production rate



Rate is likely manageable

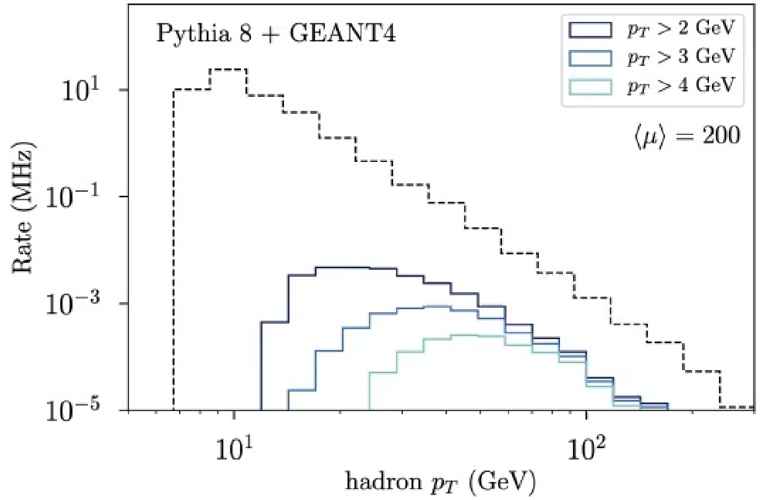
Conservative assumptions:

- Assumed 100% efficiency for tracks, *regardless of origin*
- No material veto attempted
- No isolation imposed

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

Interactions with detector material

Fold in particle production rate



Rate is likely manageable

Background rate summary:

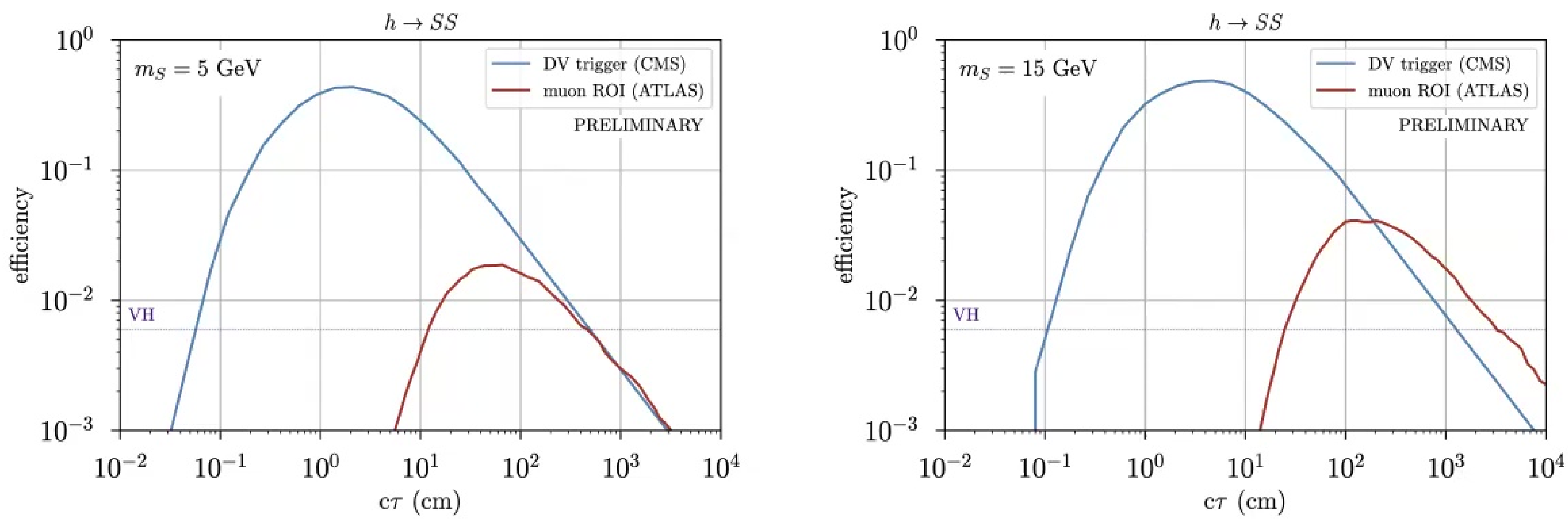
min track p_T	2 GeV	3 GeV	4 GeV
secondaries (kHz)	25	5	1
B-mesons (kHz)	0.13	0.04	0.01
fake vertices (kHz)	0.04	0.01	0.004

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

Results

Example: $h \to SS$

$\hookrightarrow$ hadrons



Qualitative gain in sensitivity appears possible

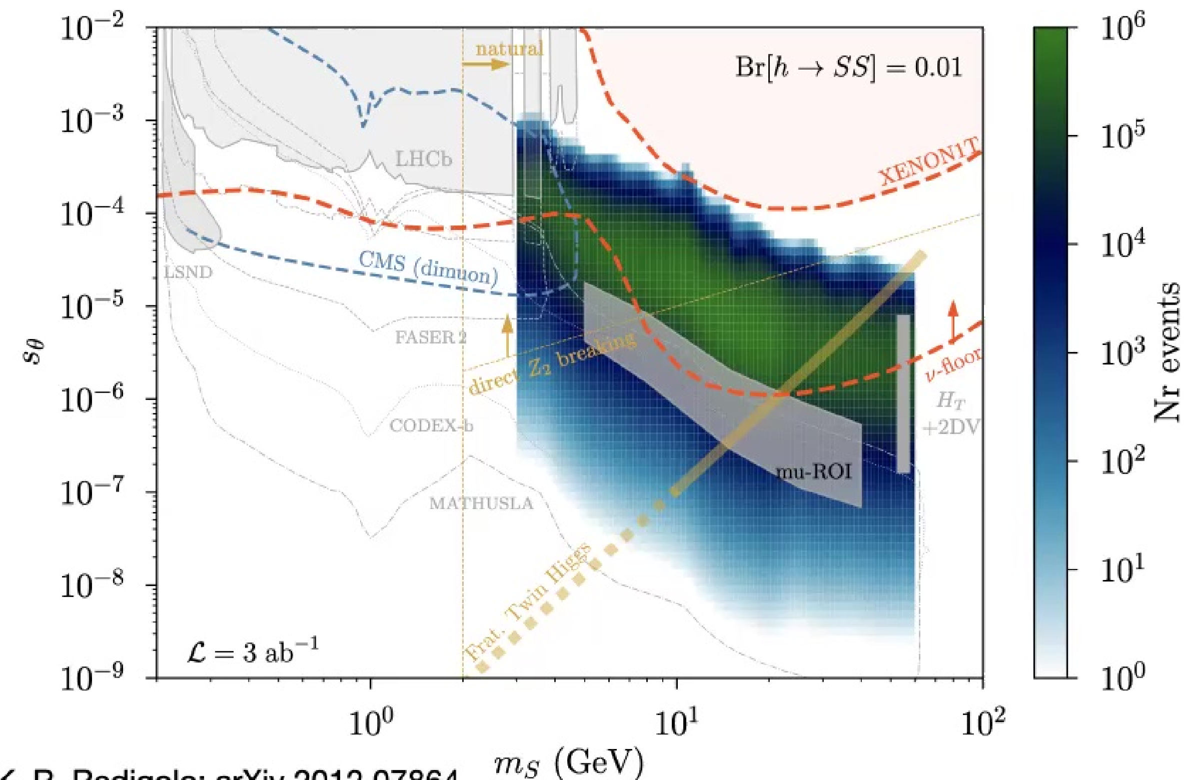
Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864
ATLAS muon ROI trigger: arXiv 1811.07370

Results

Example: $\mathcal{L}_{\rm S} \supset -\frac{1}{2}\tilde{m}_S^2 S^2 - \mu S H^\dagger H - \frac{1}{2}\lambda_{SH} S^2 H^\dagger H - V_{\rm int}(S)$

$h \to SS$

$\quad \hookrightarrow$ hadrons



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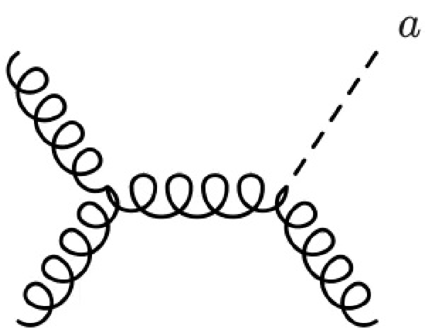
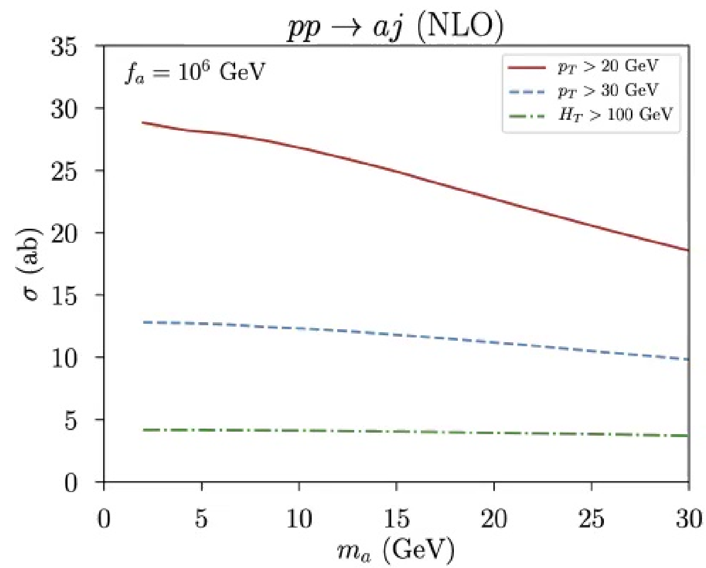
Axion-like particle

$$\mathcal{L}_a \supset -\frac{1}{2}m_a^2 a^2 - \frac{\alpha_s}{8\pi}\frac{a}{f_a}\tilde{G}G$$





Huge gluon luminosity at low invariant mass, we can get away with very high f_a

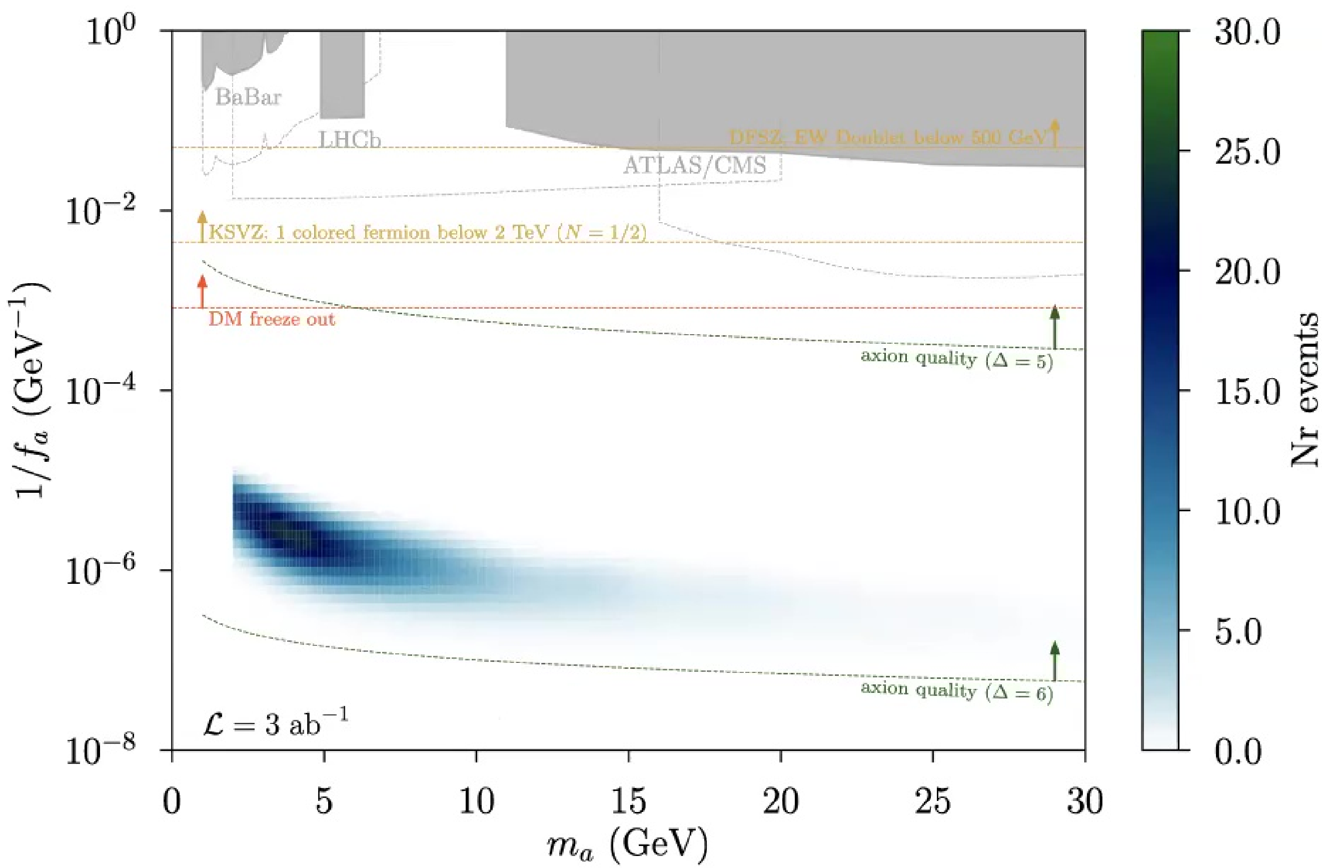
Lifetime:

$$c\tau_a \simeq 0.2 \text{ cm} \left(\frac{f_a}{10^6 \text{ GeV}}\right)^2 \left(\frac{10 \text{ GeV}}{m_a}\right)^3$$

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

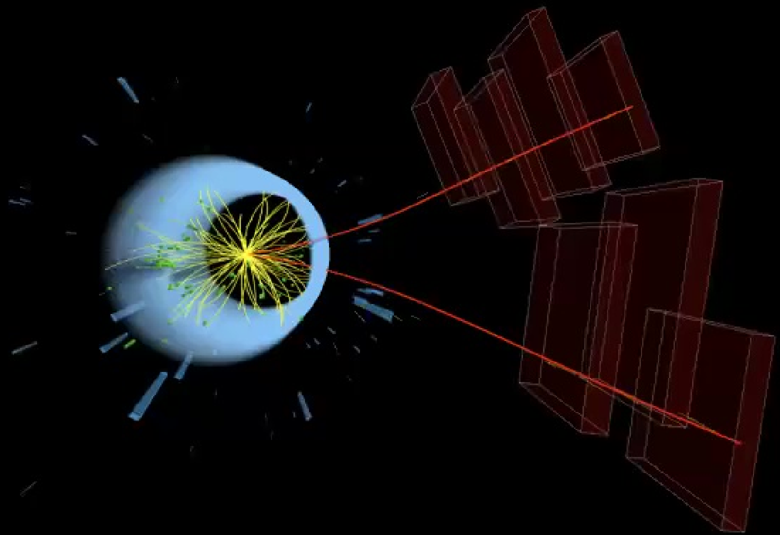
Axion-like particle

Result:



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

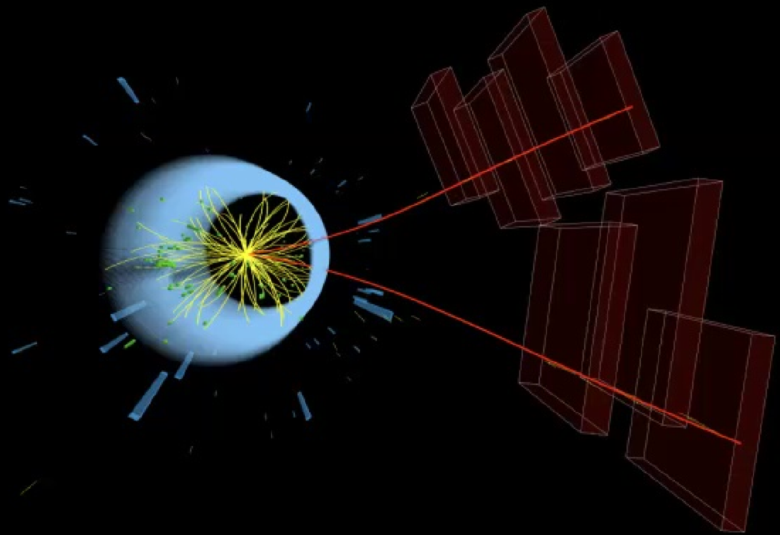
Conclusion



The LHC is a Higgs & B factory…

… Higgs and B decays are golden opportunities for beyond the Standard Model physics

Conclusion



The LHC is a Higgs & B factory…

… Higgs and B decays are golden opportunities for beyond the Standard Model physics

New (trigger) strategies and phase II upgrades could yield qualitatively new reach…

… but we must continue to innovate!