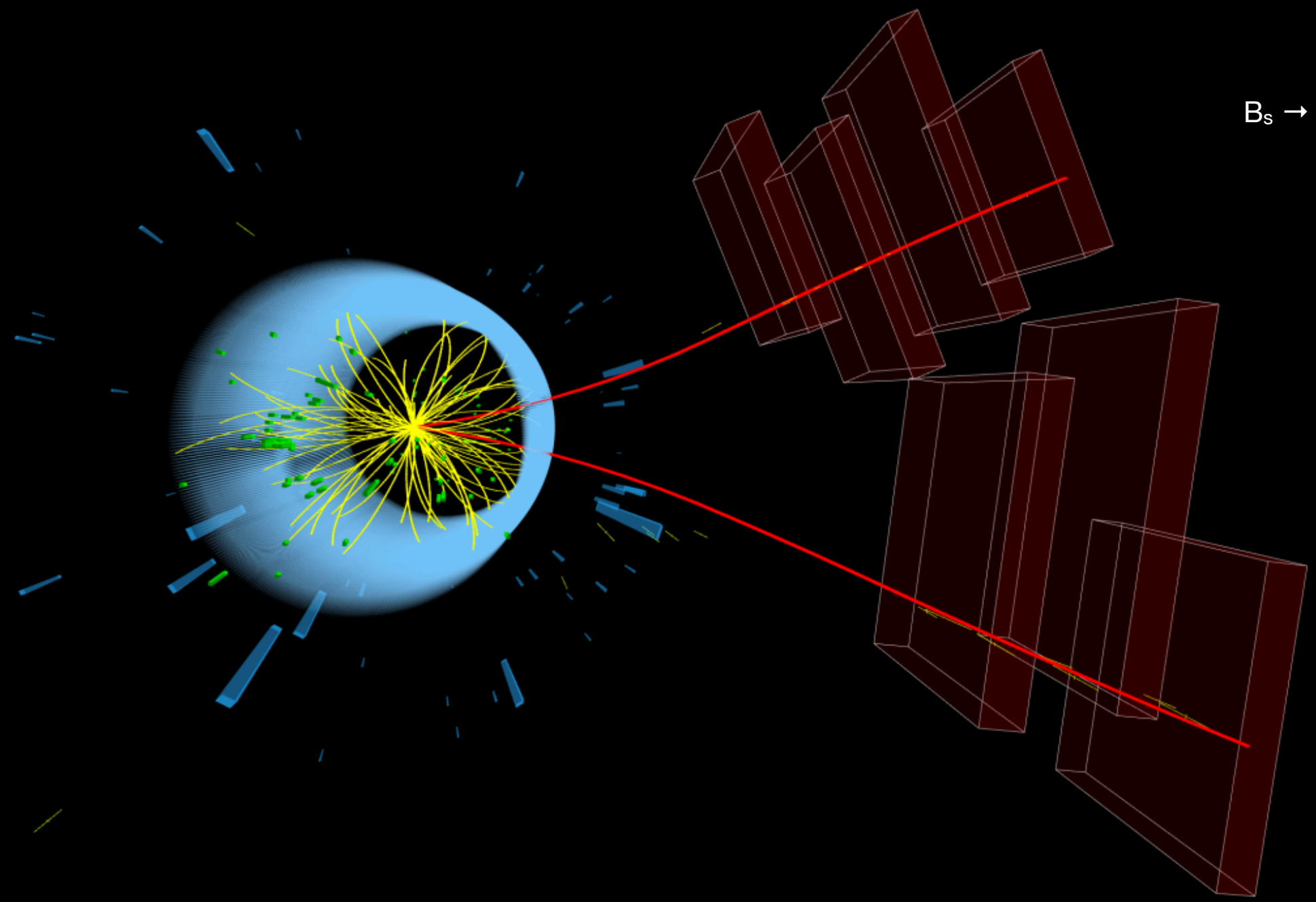
Soft Signals at the high luminosity LHC



Simon Knapen
CERN

LHC on the energy frontier

Large data set:

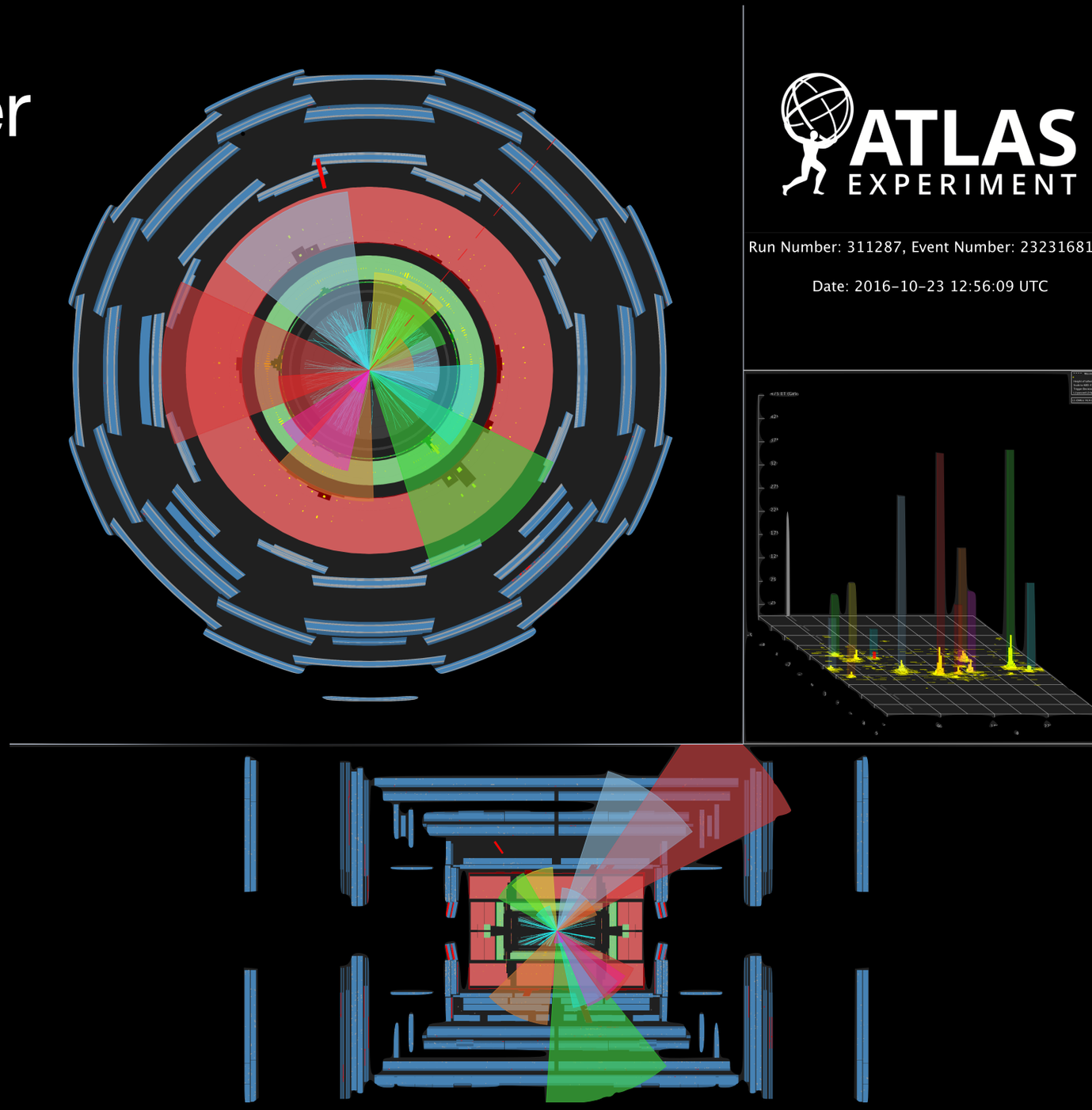
150 fb^{-1} recorded

↓

7 x 10^6 Higgs bosons produced

Analysis strategies *extremely sophisticated*

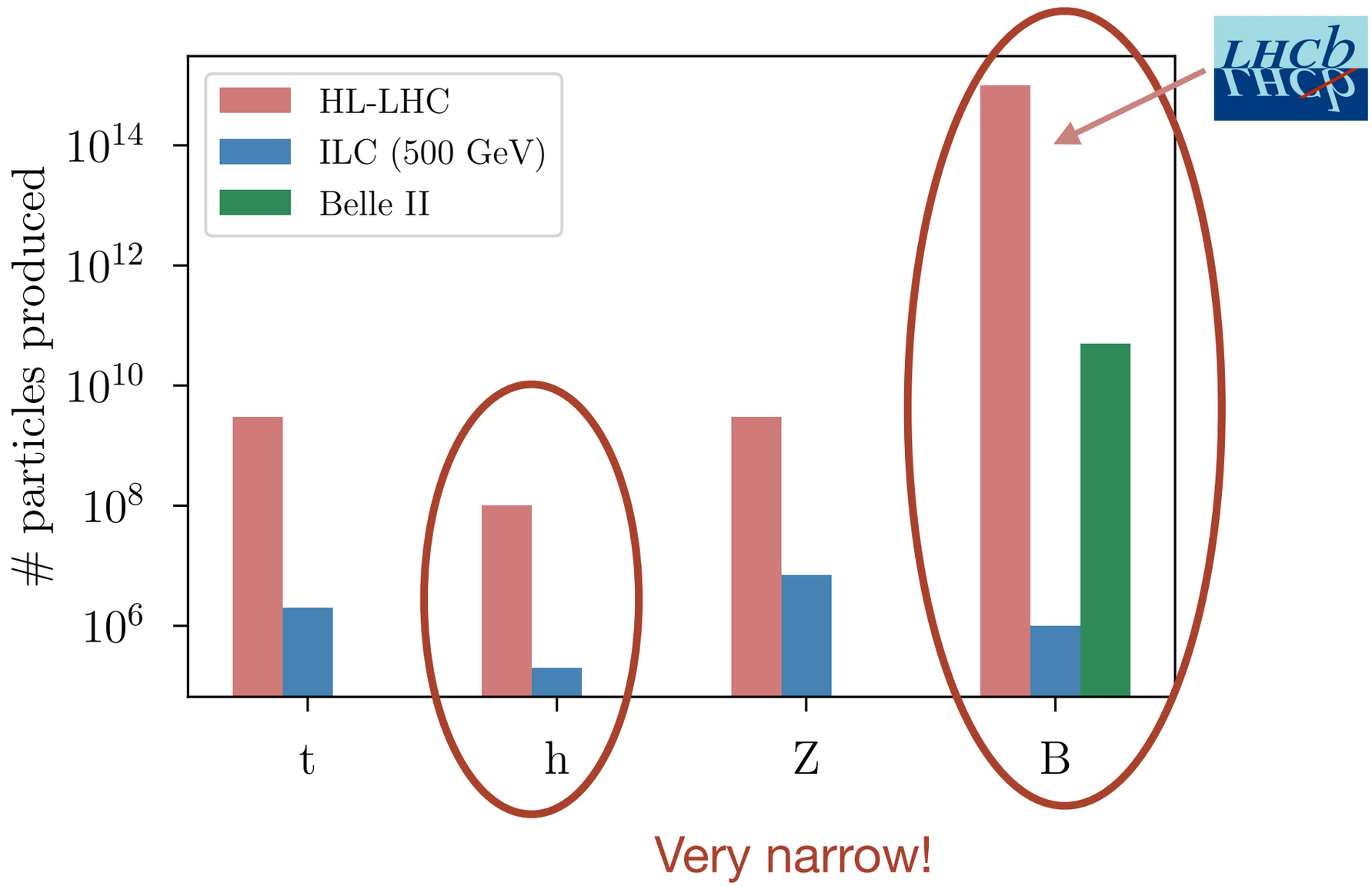
<u>This example:</u>
31 signal regions
+ corresponding control regions



N_{jets} = 13
ATLAS arXiv:1708.02794

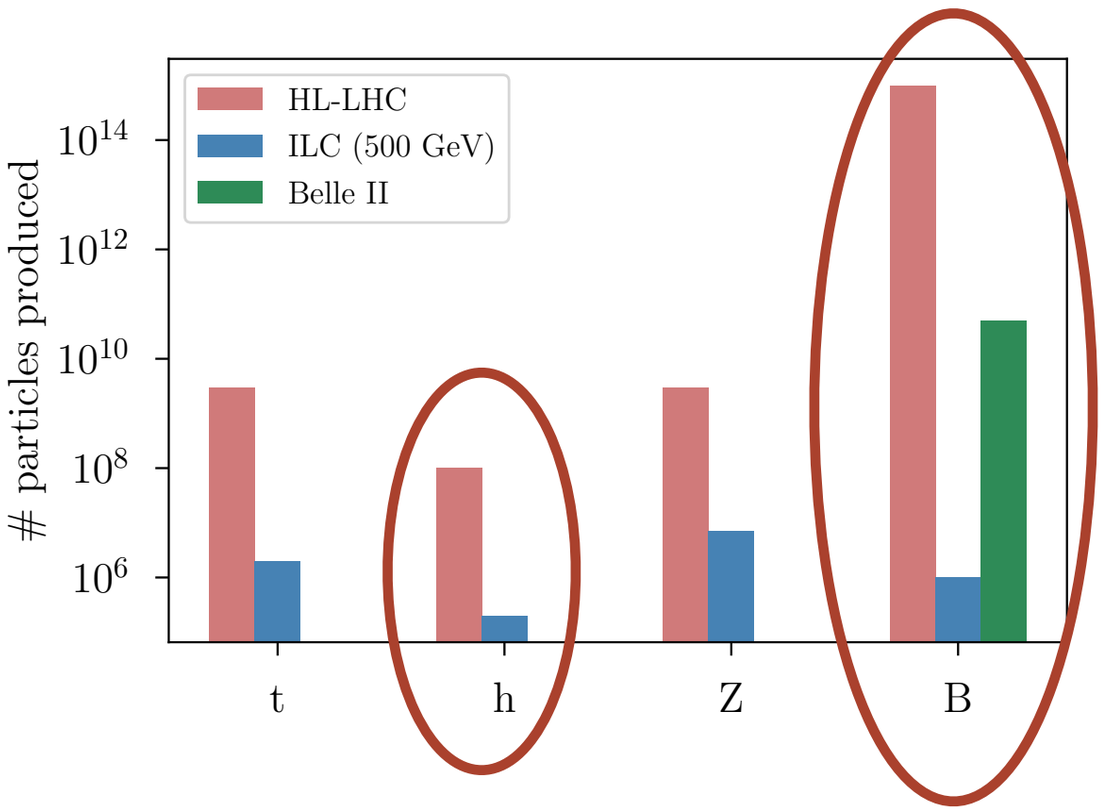
LHC on the intensity frontier

Precision measurements often challenging, but huge particle yields



LHC on the intensity frontier

Precision measurements often challenging, but huge particle yields



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)
Strong theory support	Theory support picking up	Limited theory support

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)

A sense of urgency:

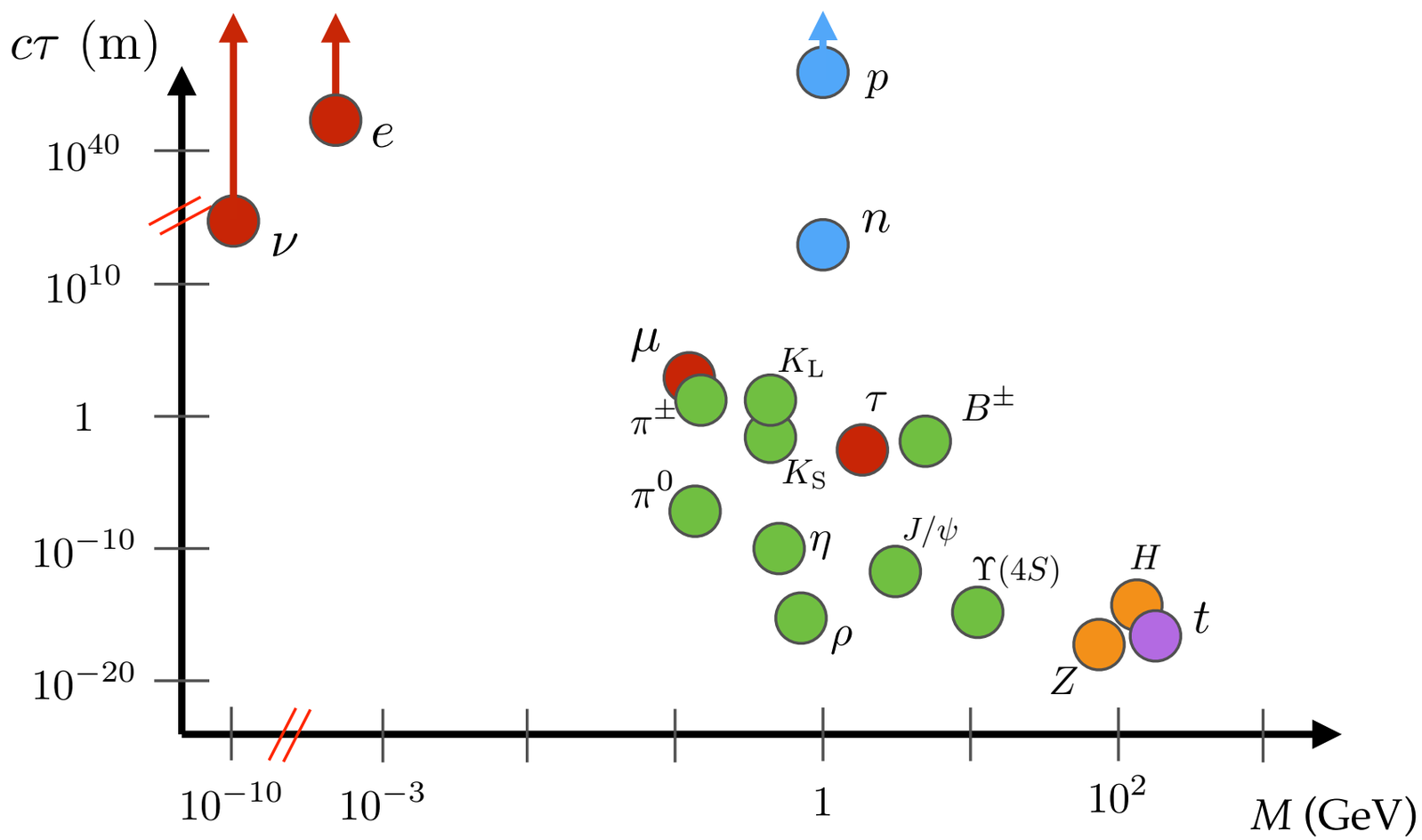
- Decisions before data taking
- Phase II upgrade design happening now

Long Lived particles

Why start with long-lived particles?

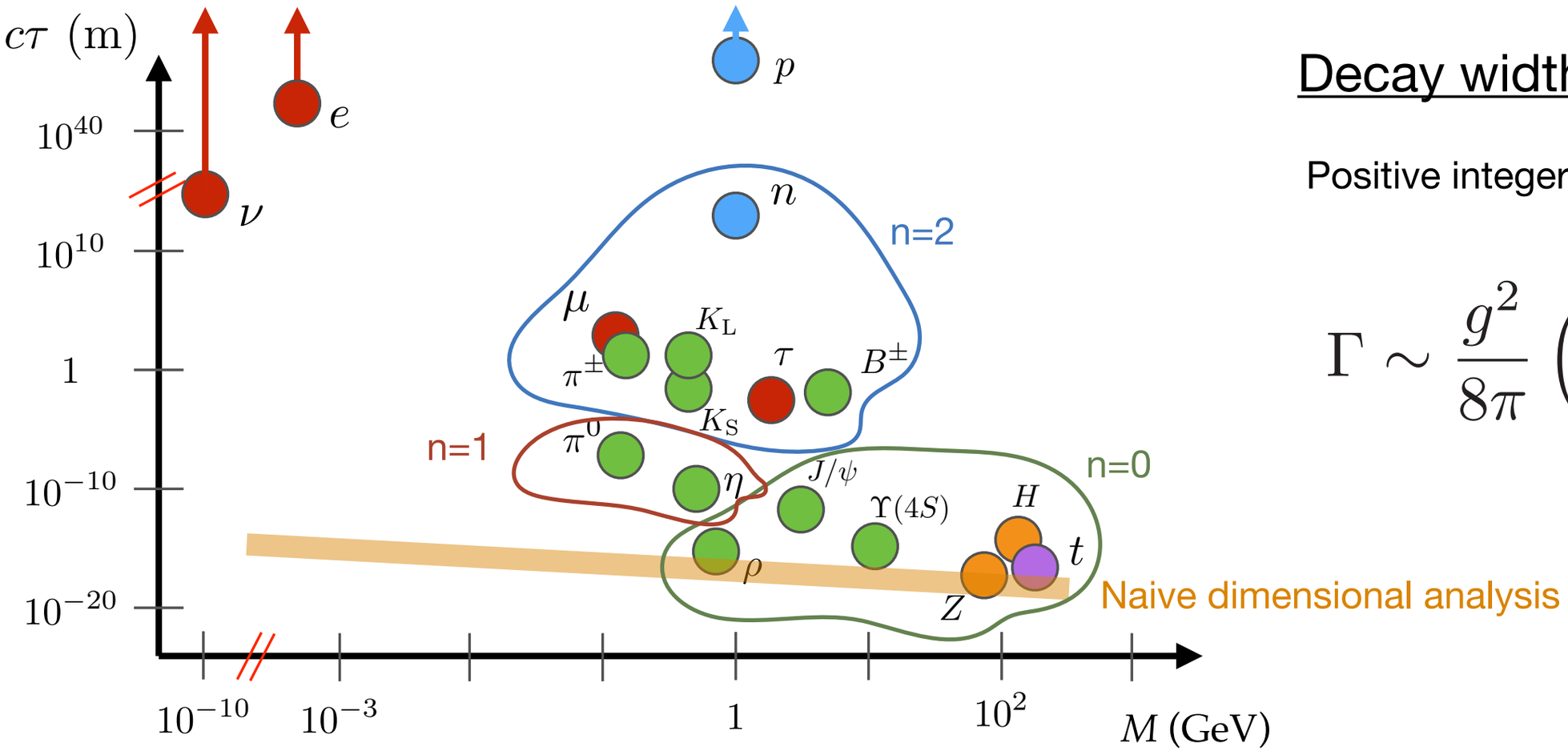
Pragmatic reason: Displaced decay gives new handle to reject backgrounds

Theory reason: Light particles tend to be long-lived



Plot by Brian Shuve

Long Lived particles



Decay width

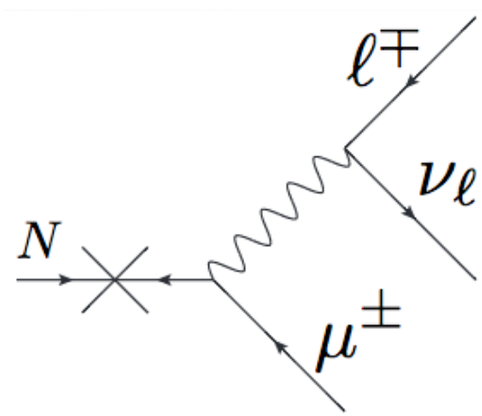
Positive integer

Particle mass

$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

Heavy mass (m_W, Λ_{QCD},…)

Beyond the Standard Model example: Sterile neutrino/Heavy Neutral Lepton



$$\Gamma \sim \frac{g^4}{64\pi^2}\left(\frac{m_N}{m_W}\right)^4 m_N$$

For mN < 5 GeV: must decay displaced

Another simple example

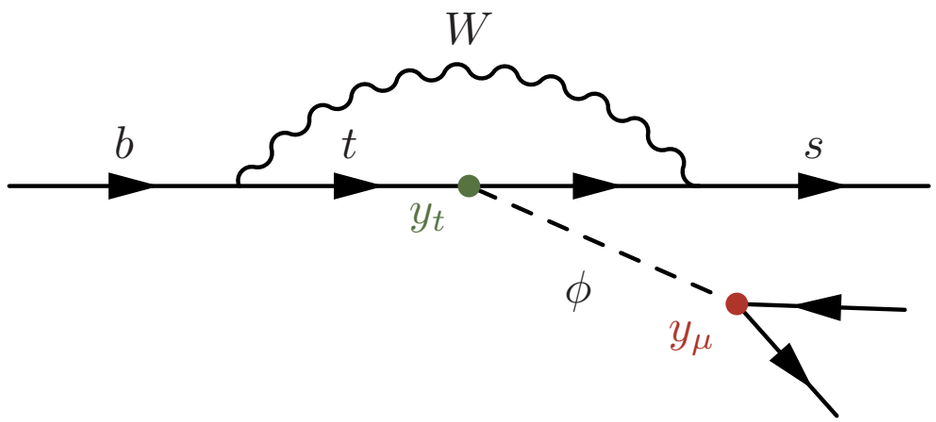
Scalar singlet extension of Higgs sector: $\mu\, \phi H^\dagger H$

(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)
…

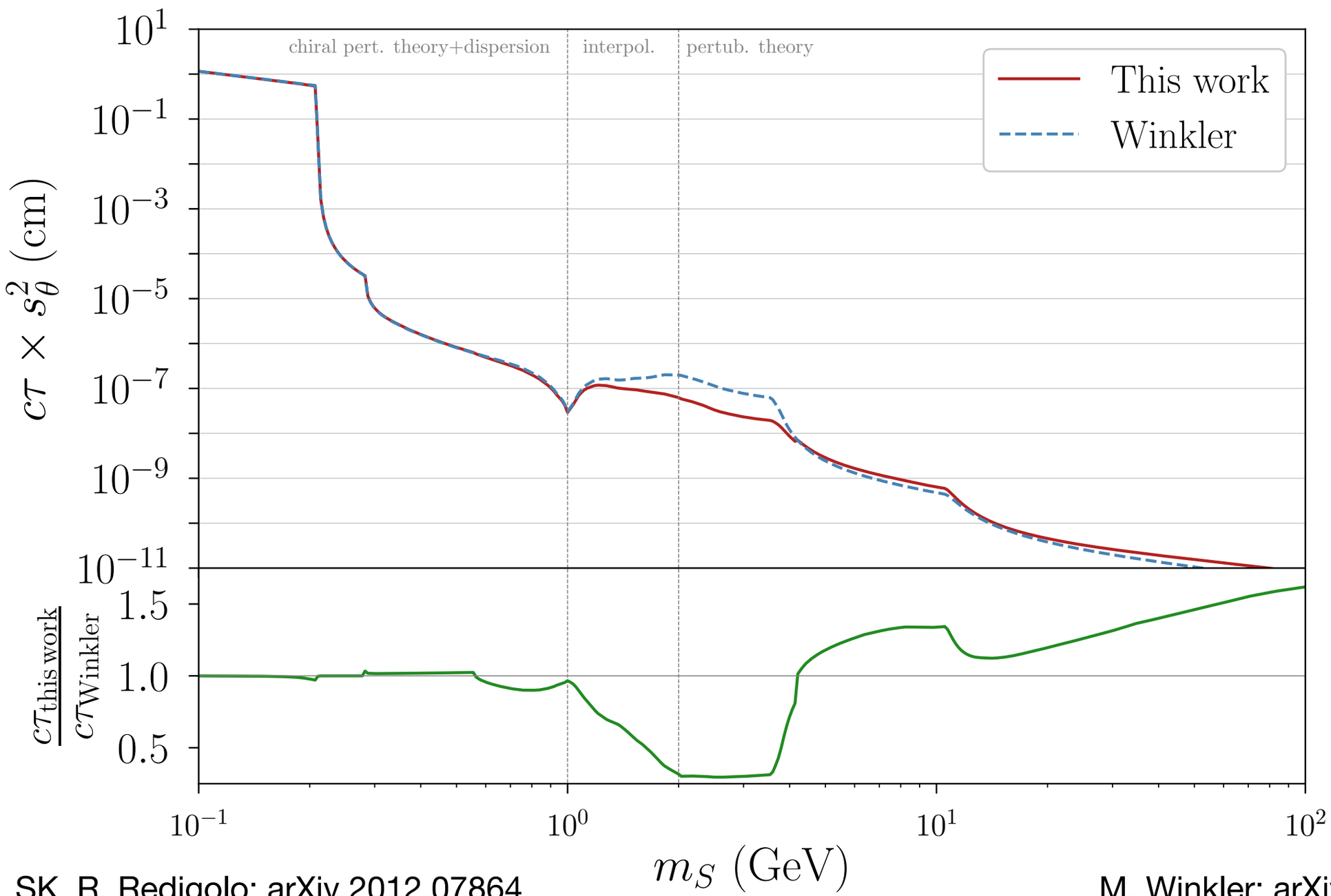


Another simple example

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

(Most minimal extension of the Standard Model)

<u>Decay</u>:

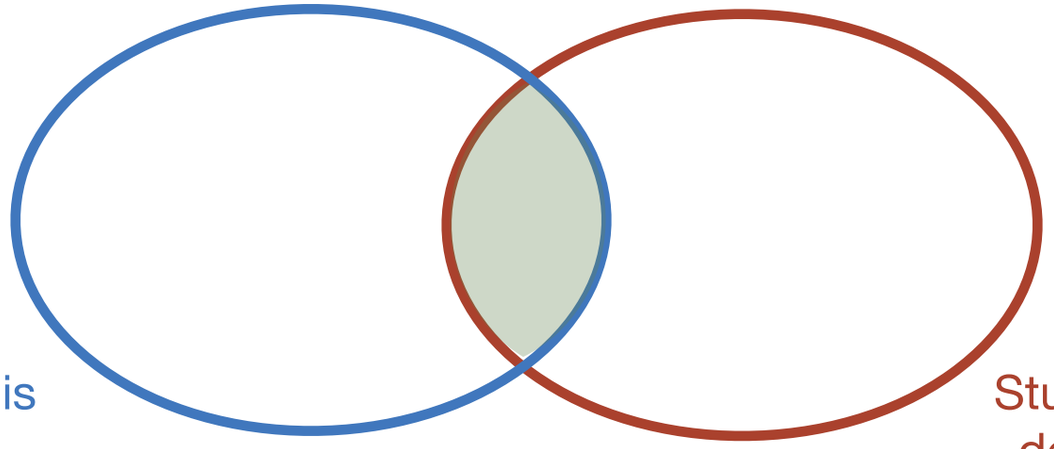


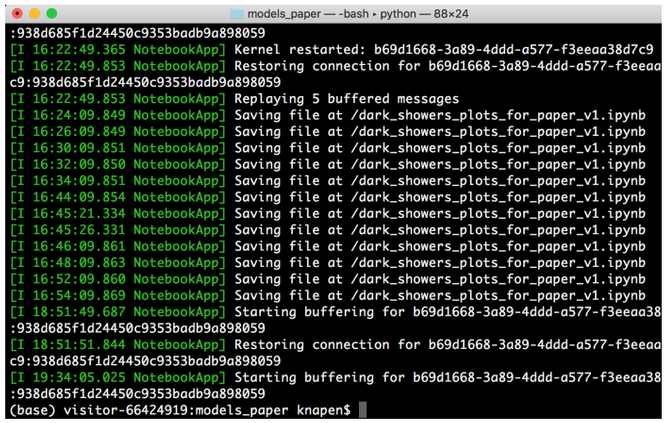
Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864

M. Winkler: arXiv 1809.01876

Things to do with the phase II upgrade

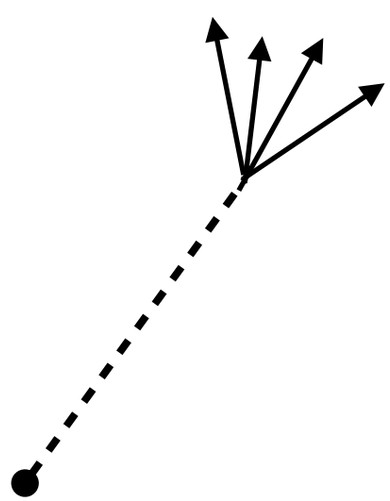
Experimental physics





Stuff that we should try to do

Theoretical physics



Displaced vertex triggers

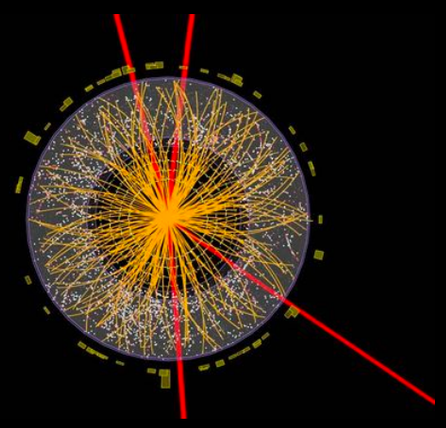
(Higgs & B decays)

CODEX-b

CODEX-b experiment

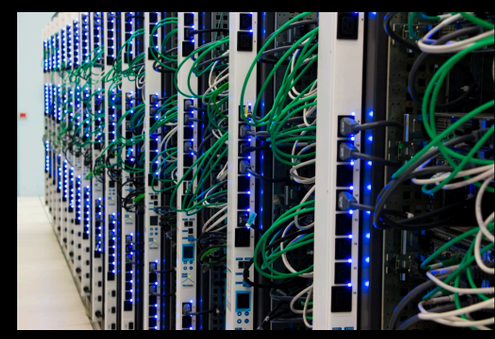
(Higgs & B decays)

Trigger basics



40 MHz

Level 1 (L1)



100 kHz

High level (HLT)

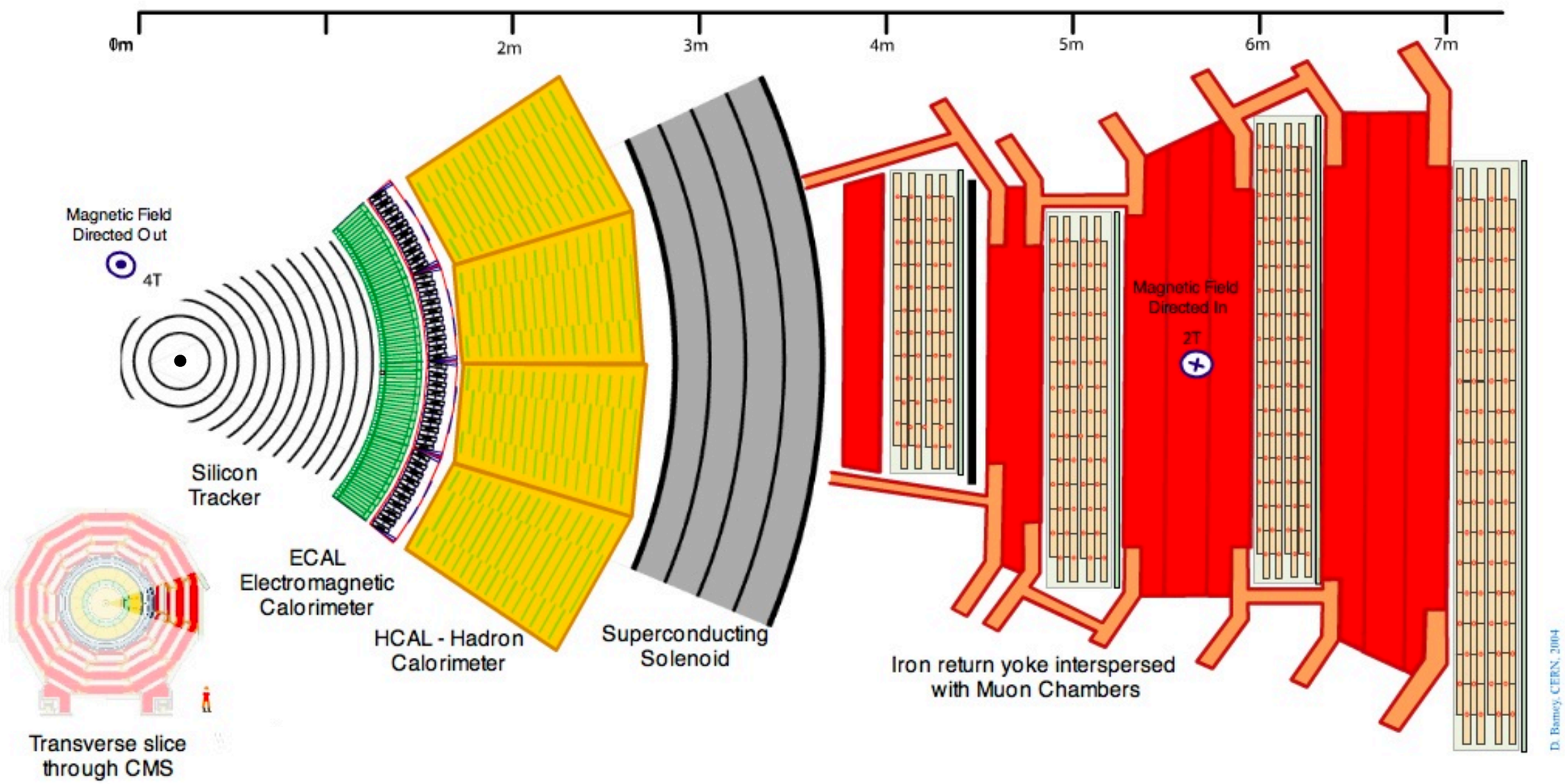
1 kHz

Only 0.0025 % of all collisions get recorded 😰

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

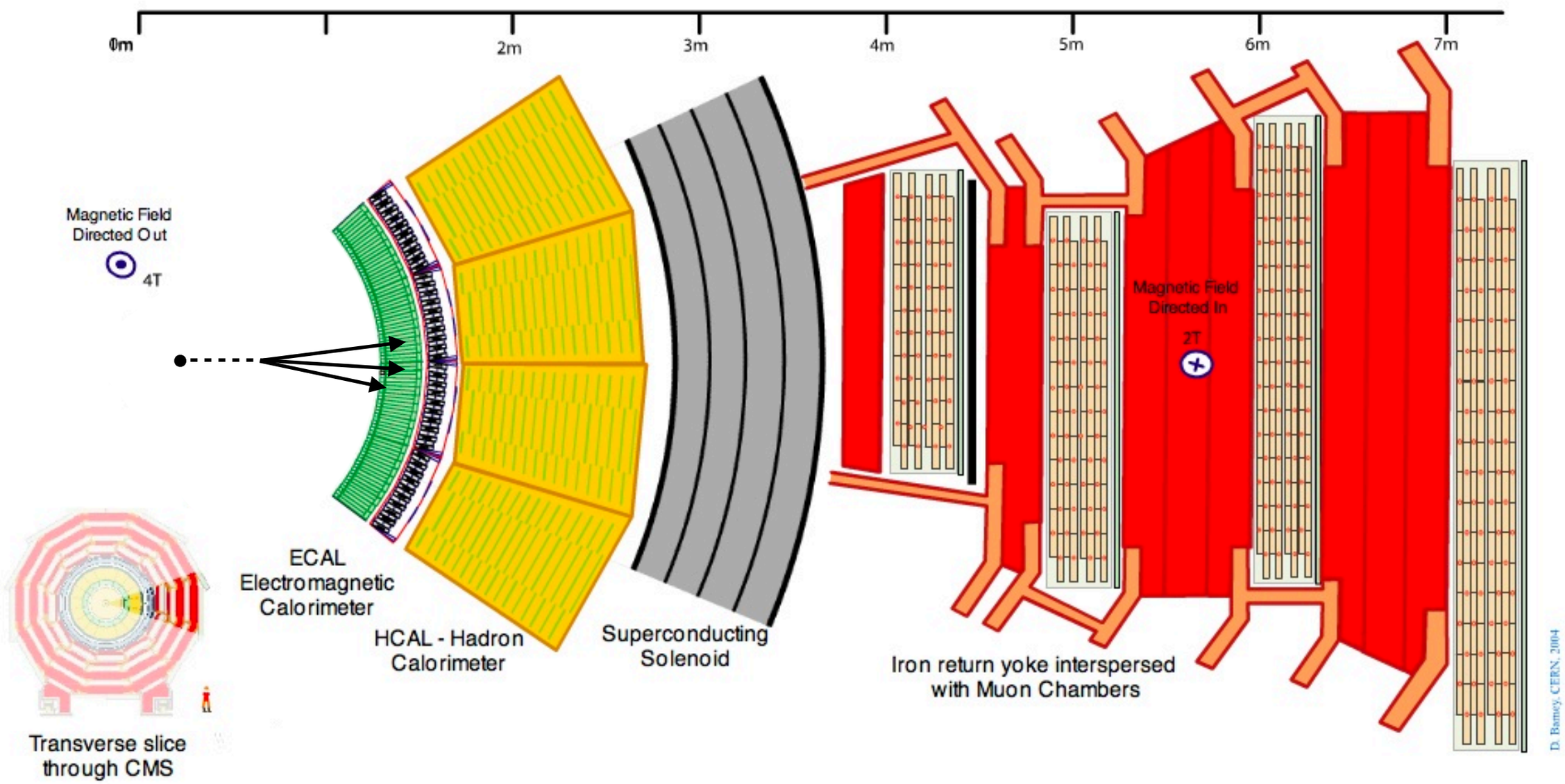
Currently only tracking at HLT step

Detector layout (CMS)



Derived from CMS Detector Slice from CERN

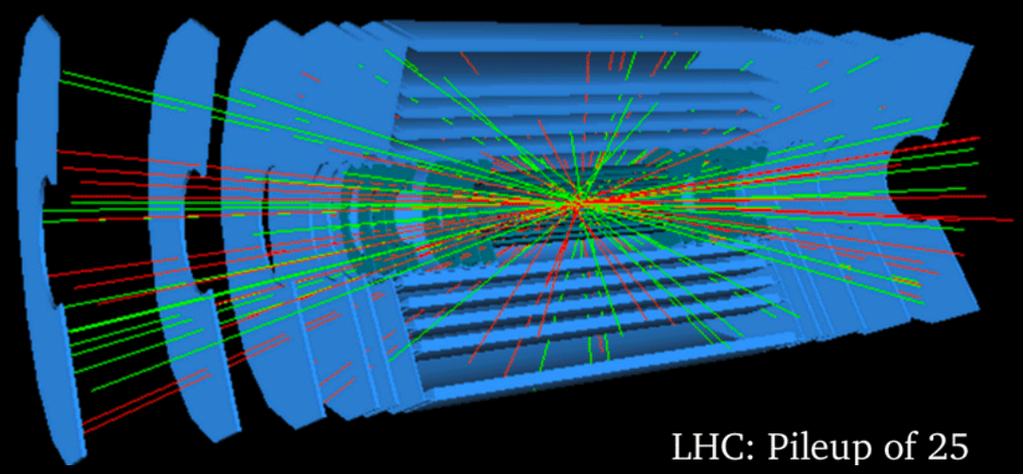
Detector layout as seen by L1 trigger

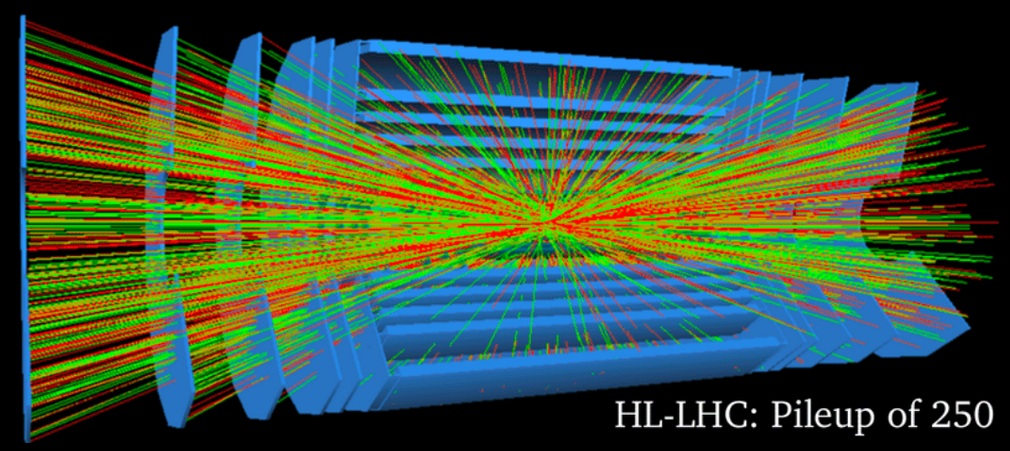


Displaced decay looks prompt to the L1 trigger, and is unlikely to be recorded

Triggers at HL-LHC

~200 collisions per event in HL-LHC conditions





ATL-UPGRADE-PROC-2012-003

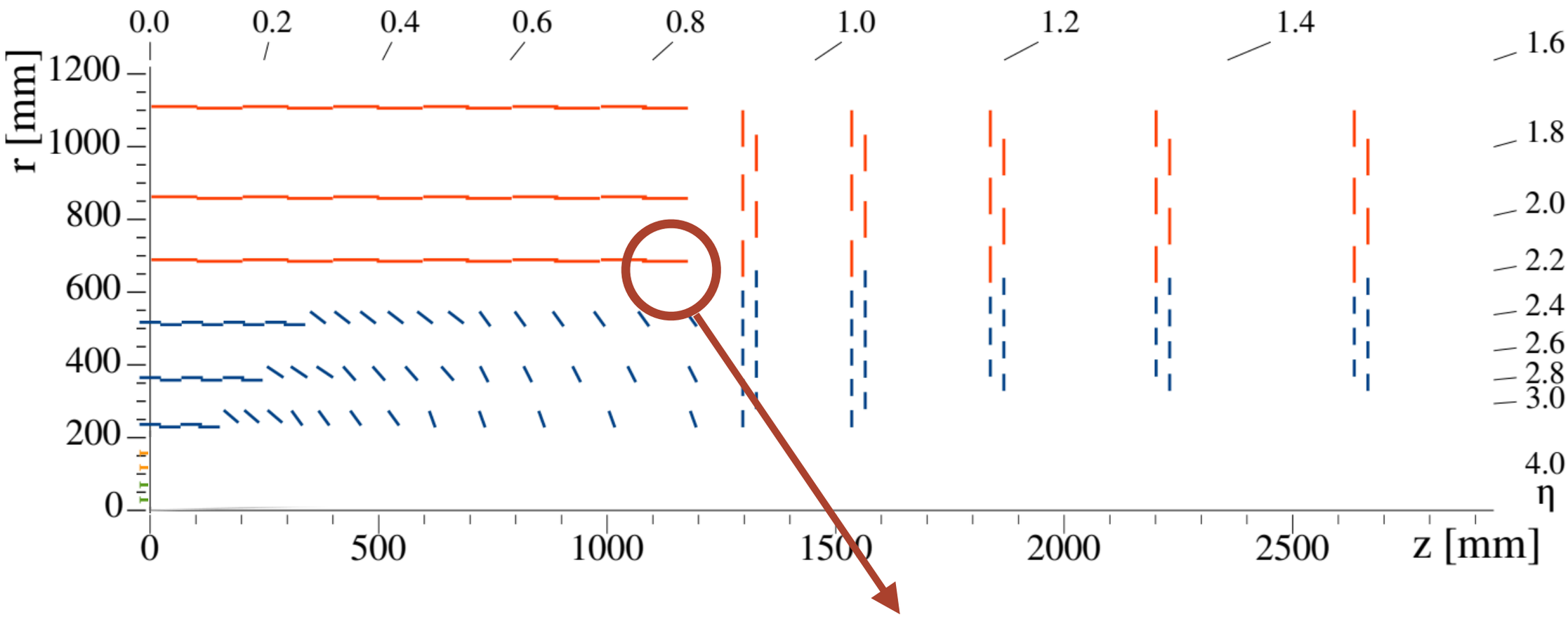
Major upgrades to the trigger being developed:

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

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

CMS Level 1 track trigger

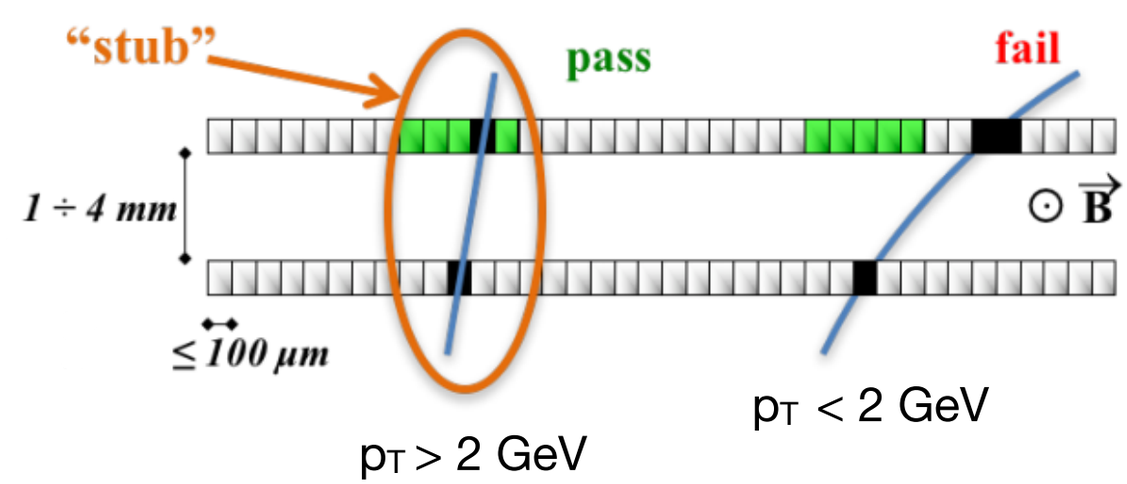
Phase II tracker layout



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

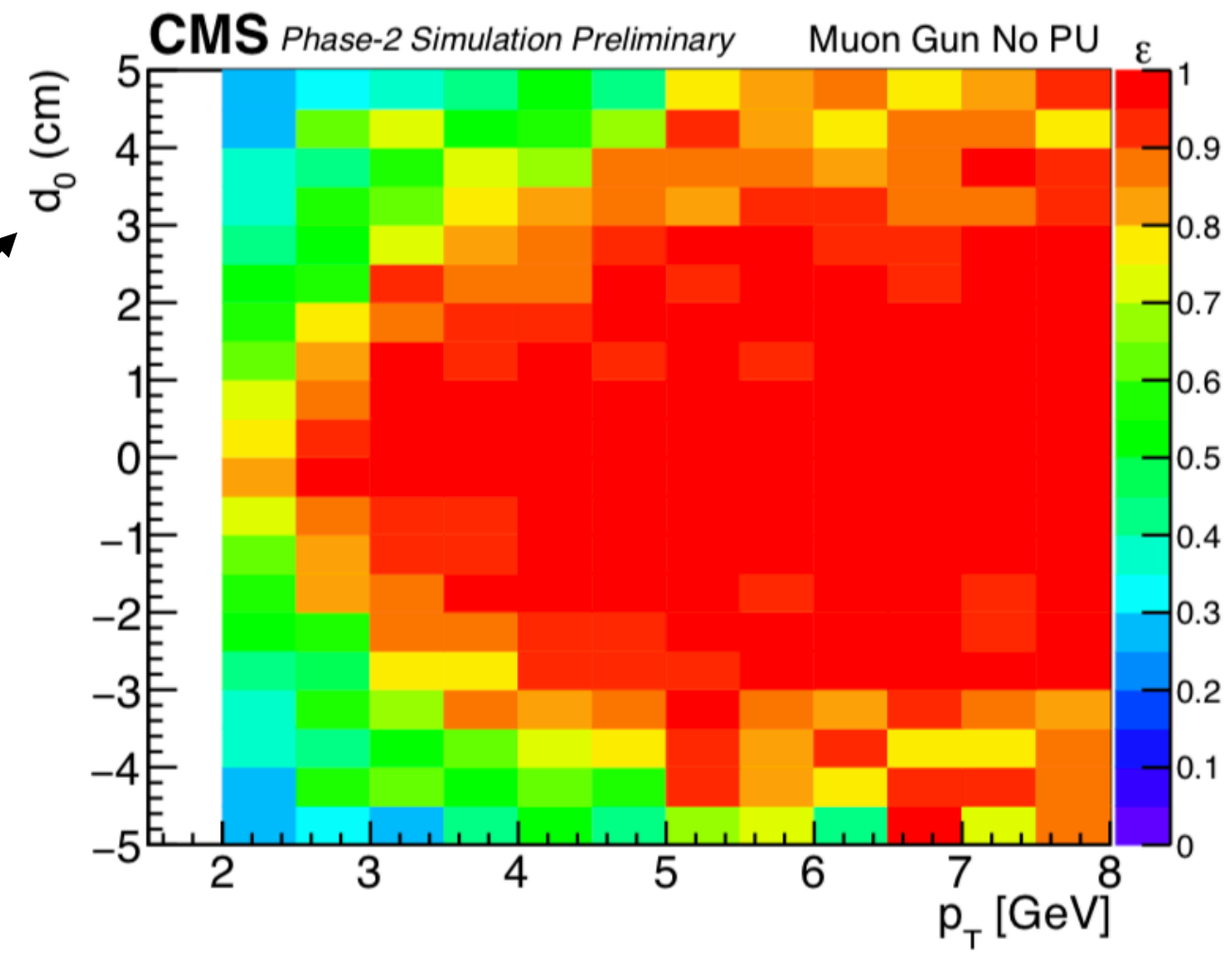
Displaced tracks

Key point: For moderate displacements, stubs are still reconstructed

↓

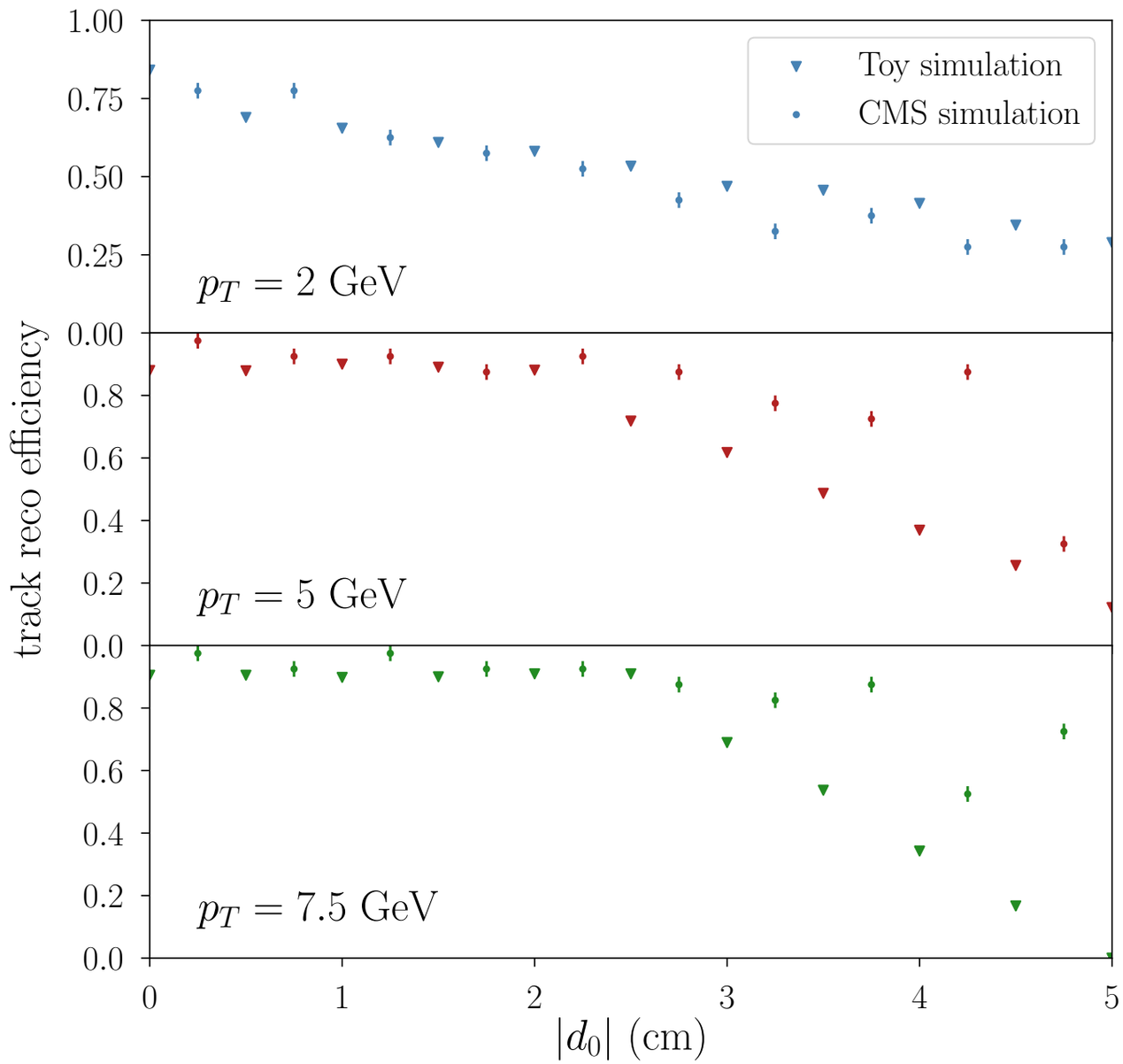
In principle, track trigger could find displaced tracks

Impact parameter in the transverse plane



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

Toy detector simulation



Impact parameter in transverse plane

<u>Procedure:</u>

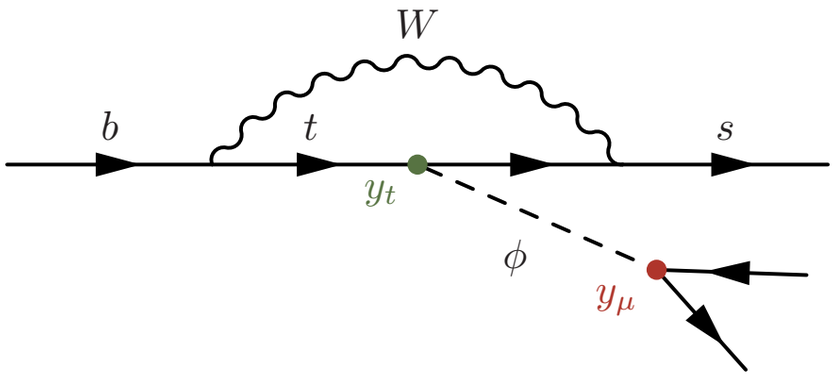
1. Propagate track
   (including multiple scattering)
2. Find the stubs
   (smearing for resolution)
3. Fit a helix to the stubs
   (require at least 5 stubs)
4. Reconstruct a vertex

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

Signal & Background

<u>Signal:</u> displaced dimuon resonance

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



<u>Backgrounds:</u>

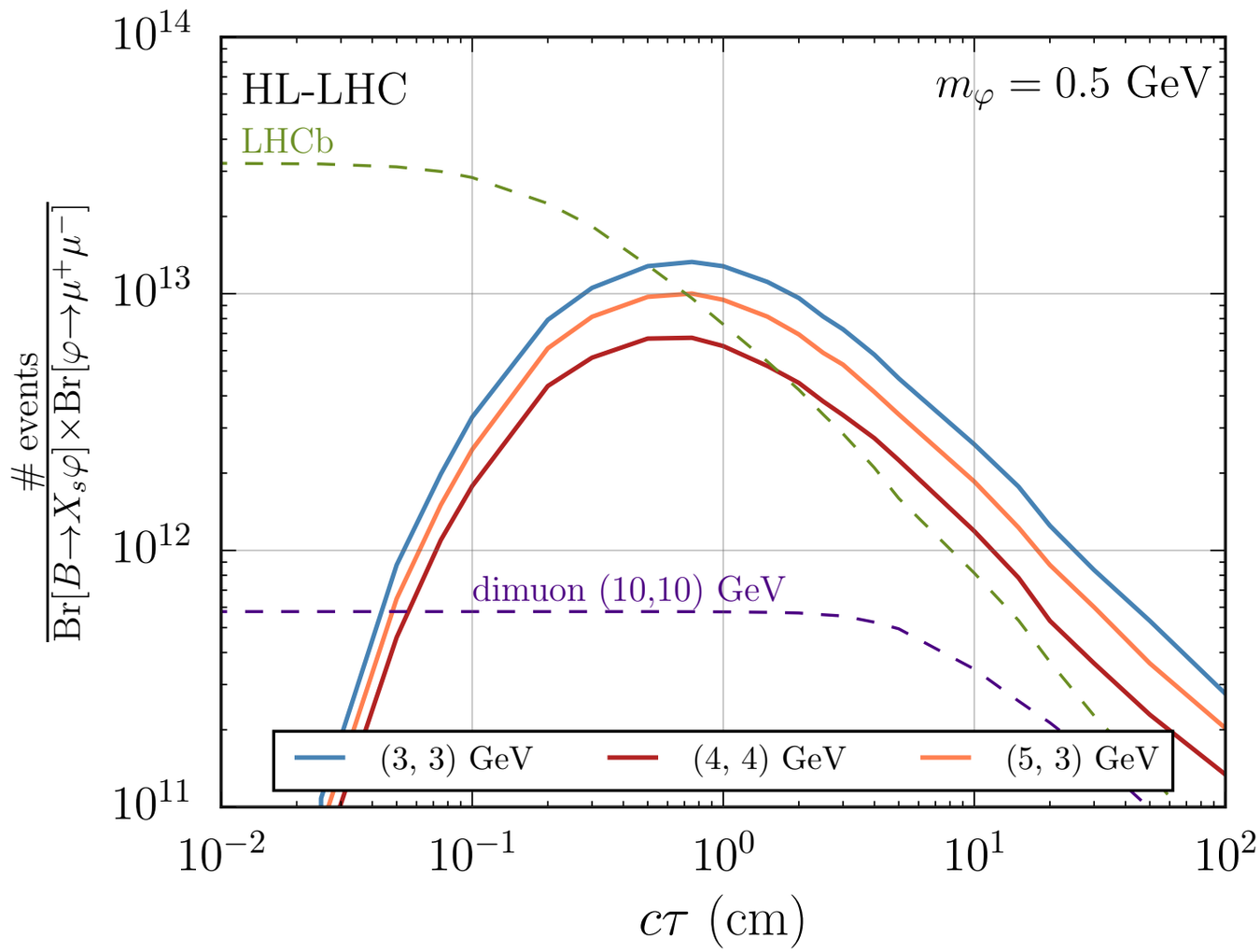
- Fake vertices → Vertex quality & muon matching
- Kaons $(K_S \to \pi^+\pi^-)$ → Muon matching
- B-mesons → Cut vertex radial distance (L_{xy}>1.5 cm)

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

Y. Gershtein, SK: arXiv 1907.00007

Trigger yield

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



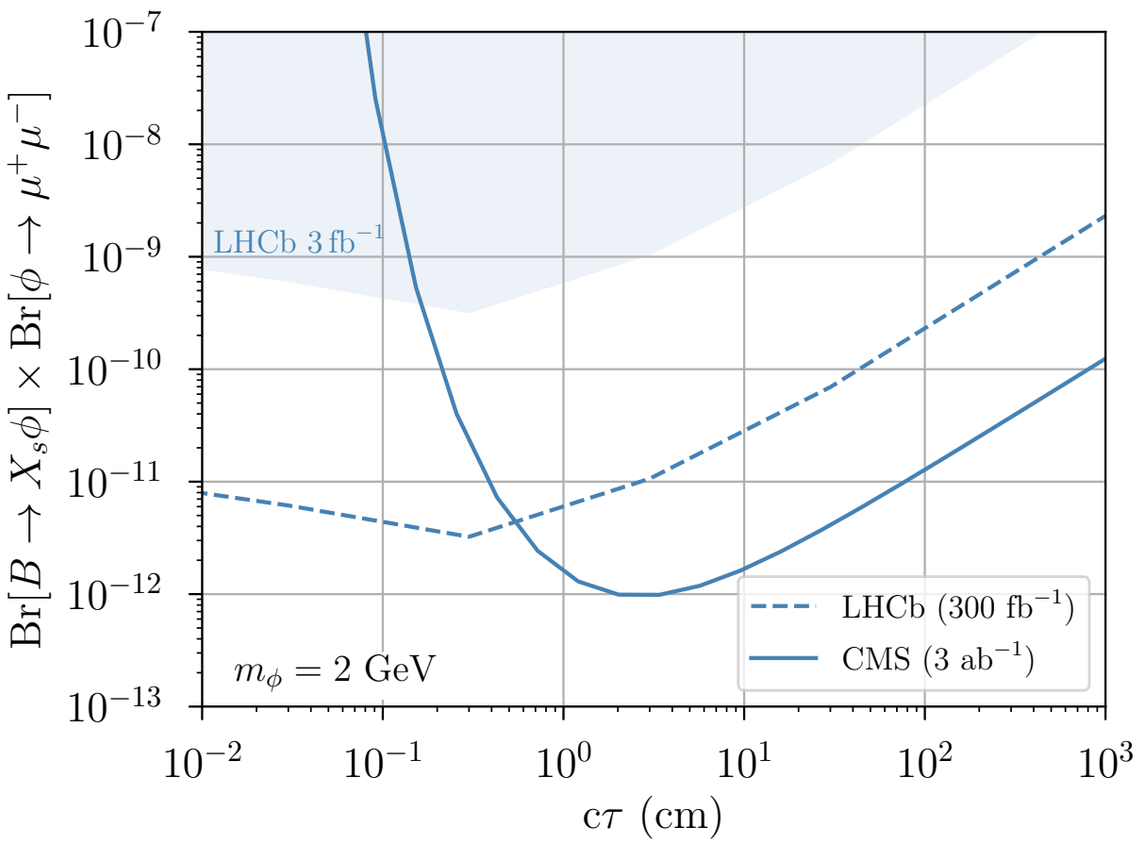
Competitive with LHCb, much better than a (generous) normal dimuon trigger

Y. Gershtein, SK: arXiv 1907.00007

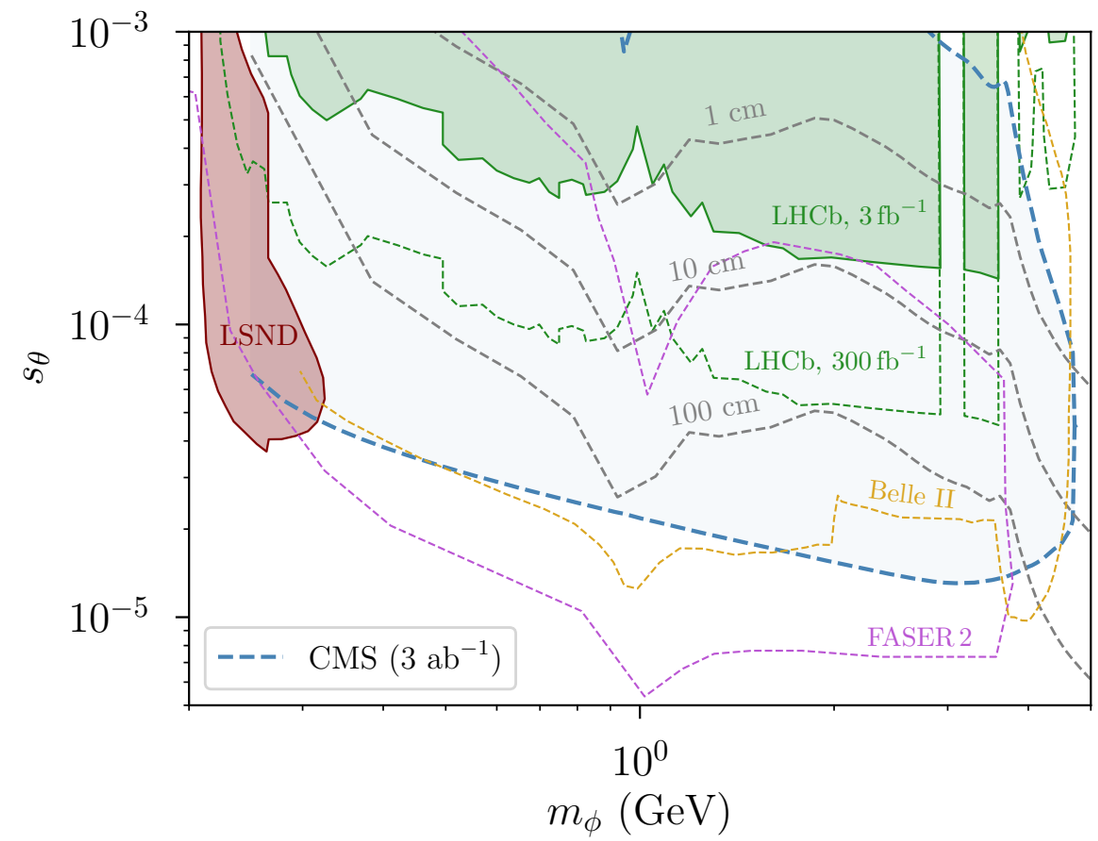
Projected sensitivity

Reach:

Model independent



Scalar mixing with Higgs



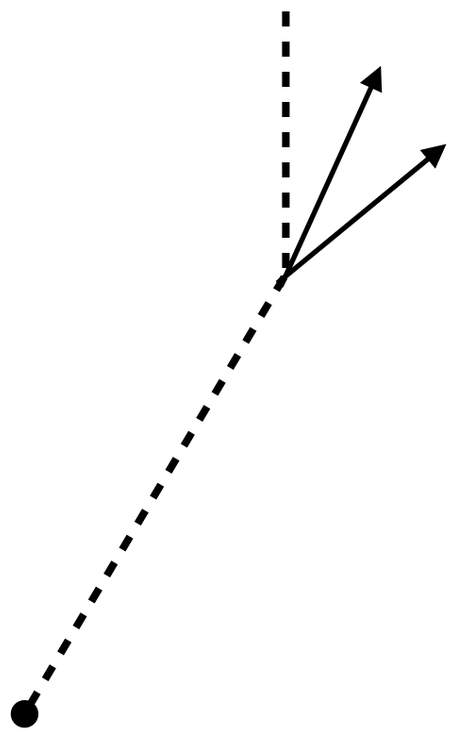
CMS reach is a bit optimistic, since “junk” backgrounds are not modeled

LHCb reach (optimistically) rescaled from current limits

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

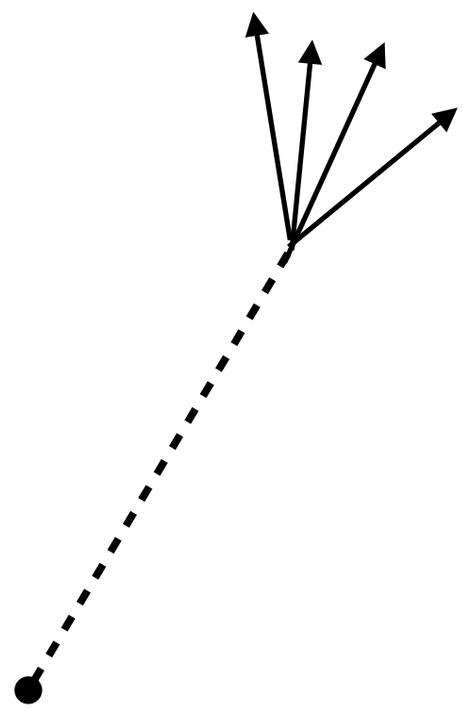
Other applications

DV + MET



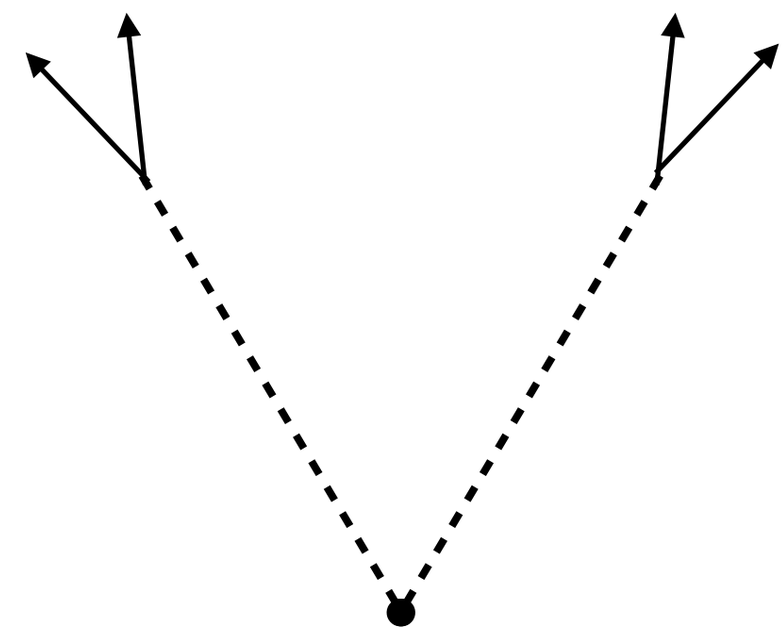
Heavy Neutral Leptons,
Inelastic Dark Matter

Multi-track DV



Axion-like particles
Exotic Higgs decays

Double DV

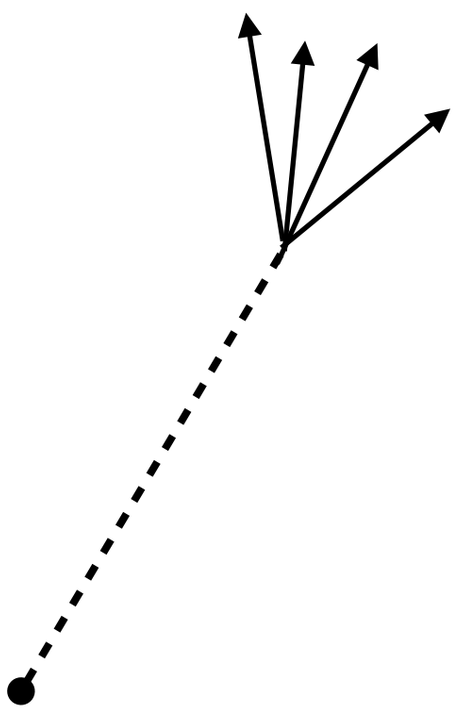


Dark Showers
Pair production of LLPs

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

Other applications

Multi-track DV



Axion-like particles
Exotic Higgs decays

<u>Selection</u>

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

<u>Backgrounds</u>

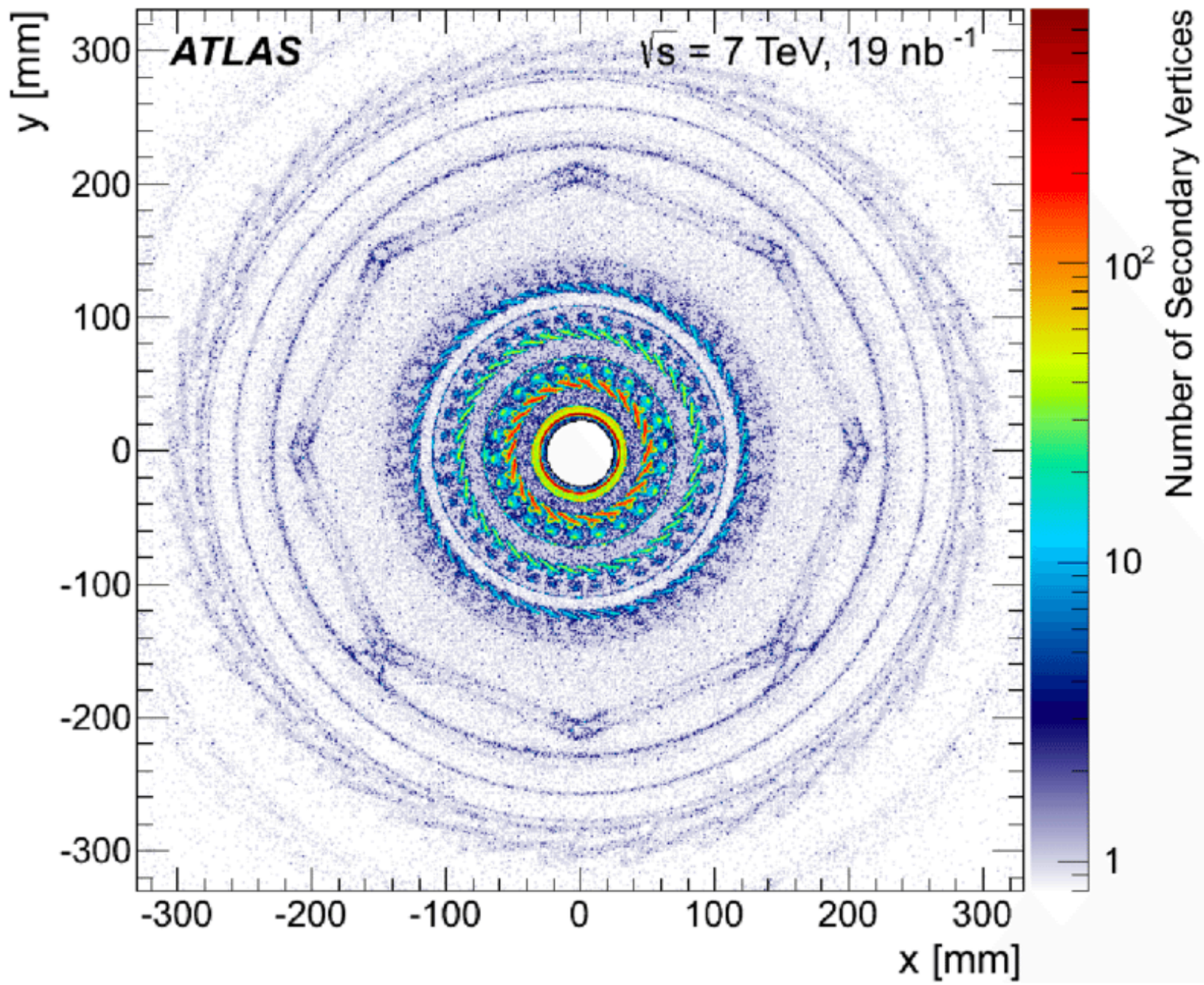
- Fake vertices → ≥ 4 tracks
- B-mesons → Vertex distance
- Material interactions → ??

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

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

Material interactions

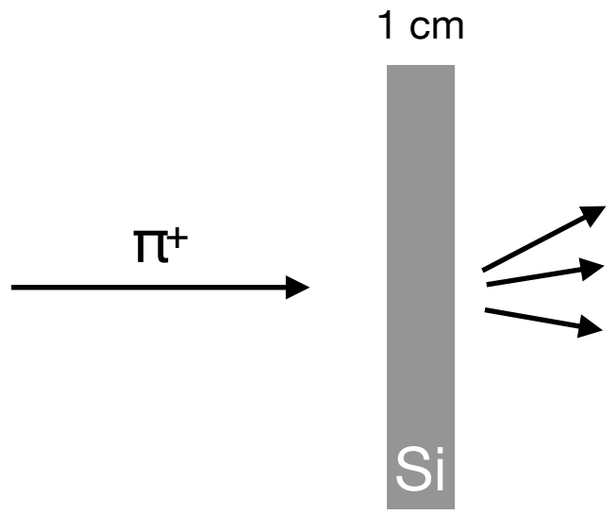
Standard Model particles create secondaries in detector material

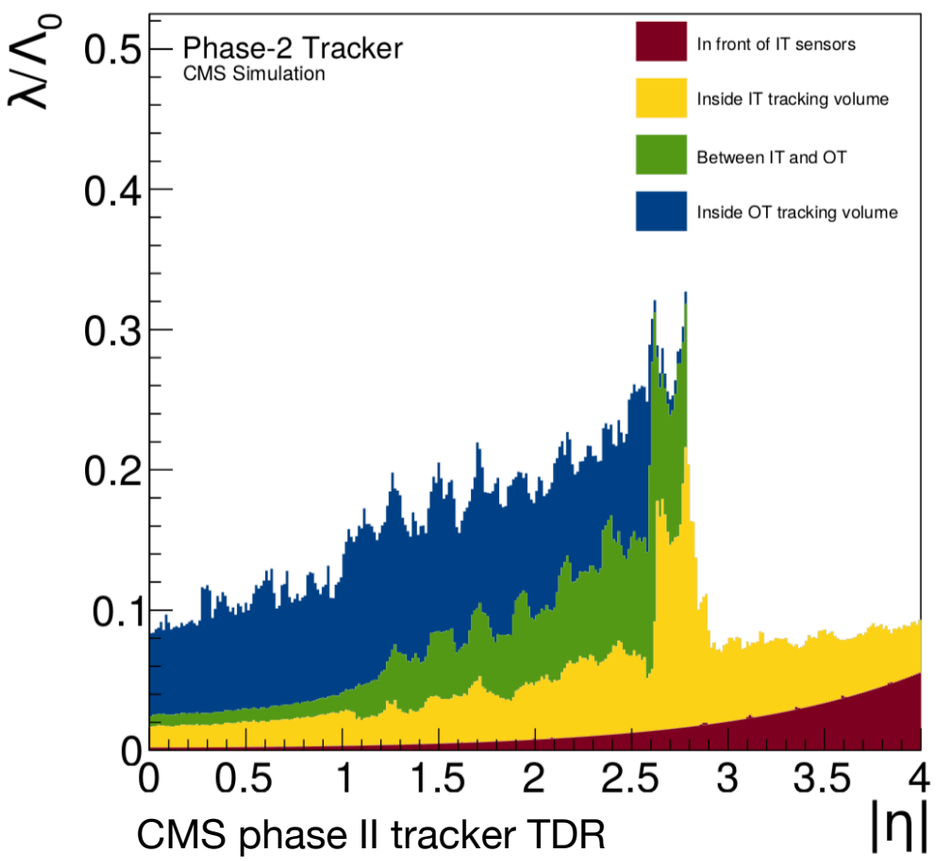


Must verify that this does not swamps the trigger bandwidth!

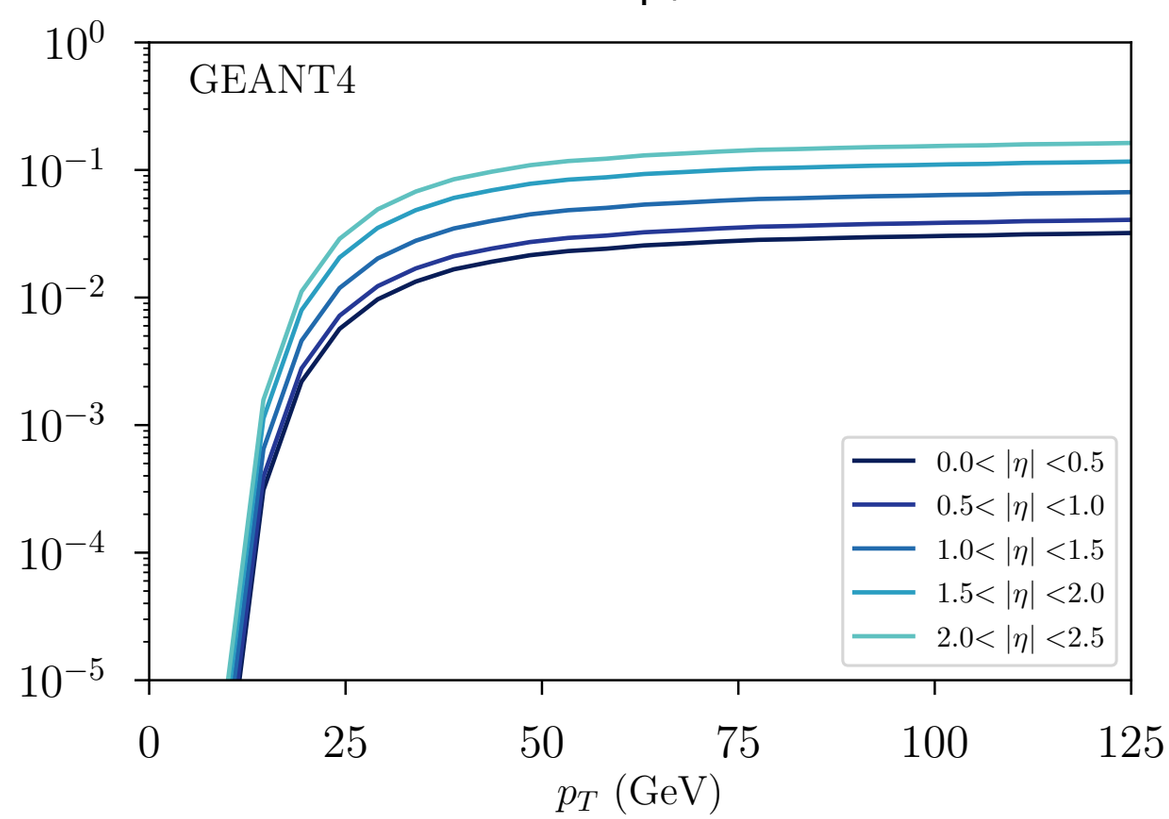
Interactions with detector material

Pion gun in GEANT4





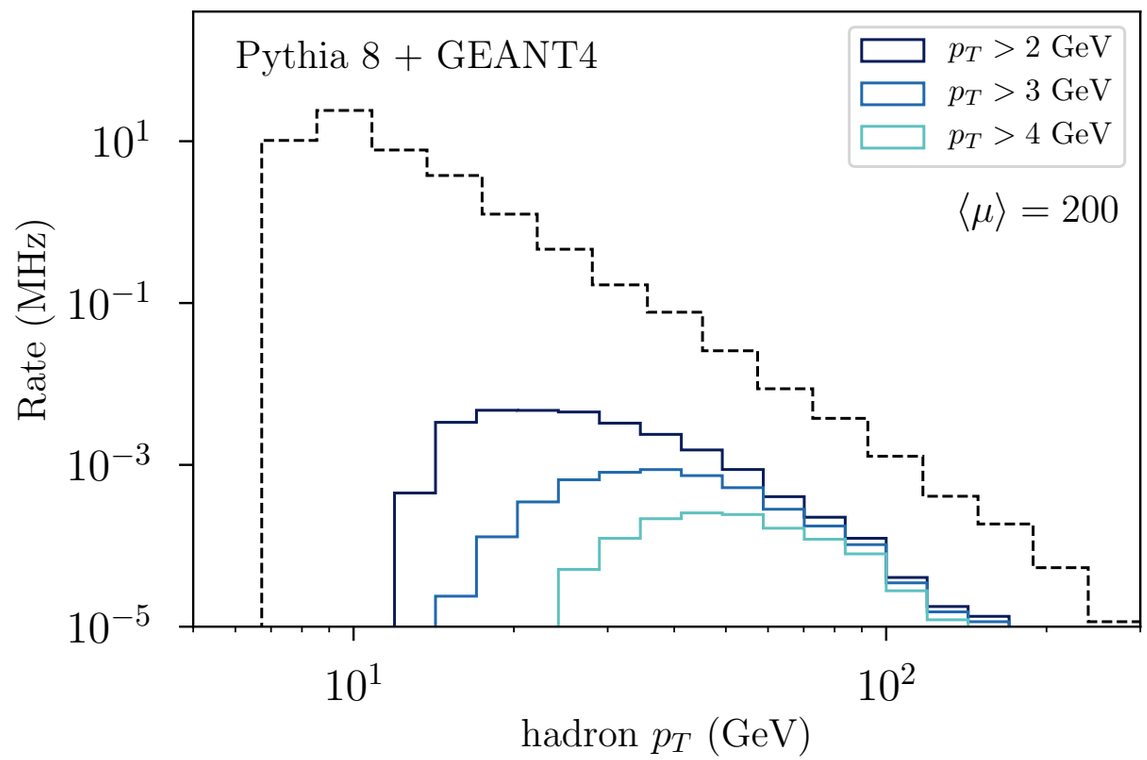
4 tracks with p_T > 2 GeV



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

Interactions with detector material

Fold in particle production rate



Rate is likely manageable

Background rate summary:

Conservative assumptions:

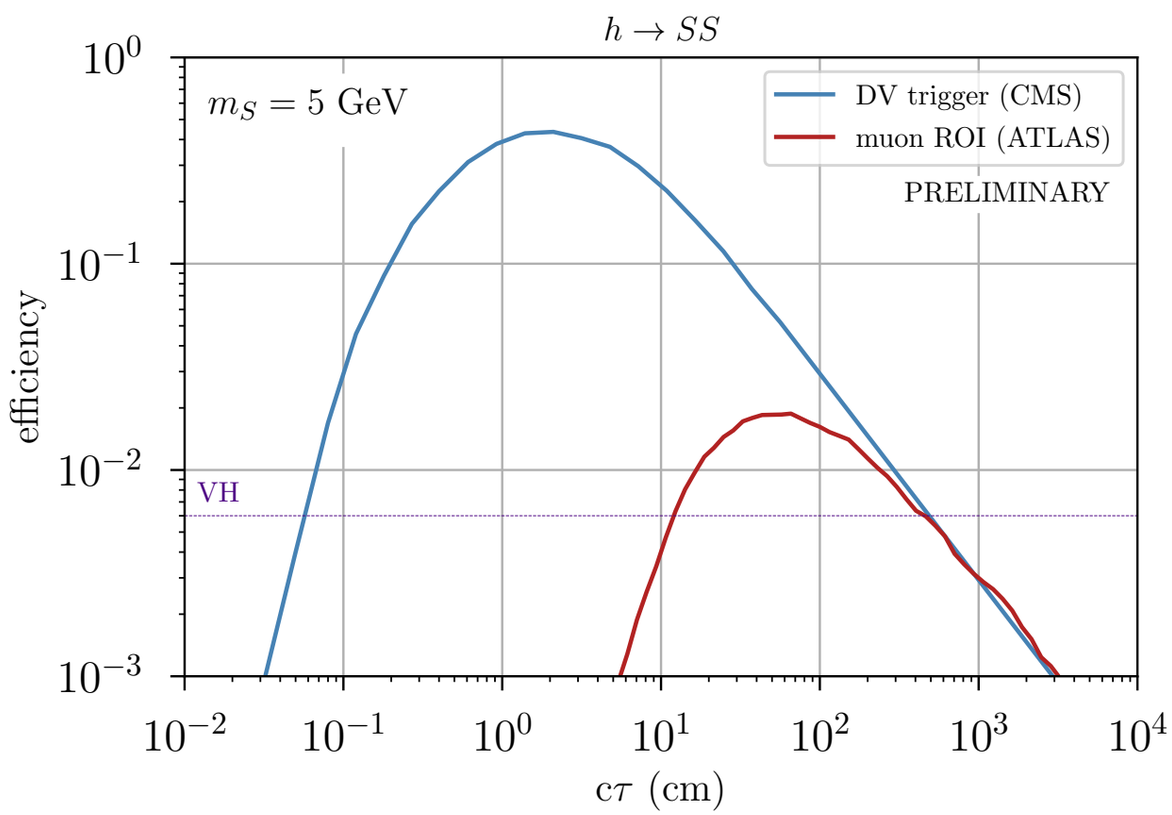
- Assu
- No m
- No is

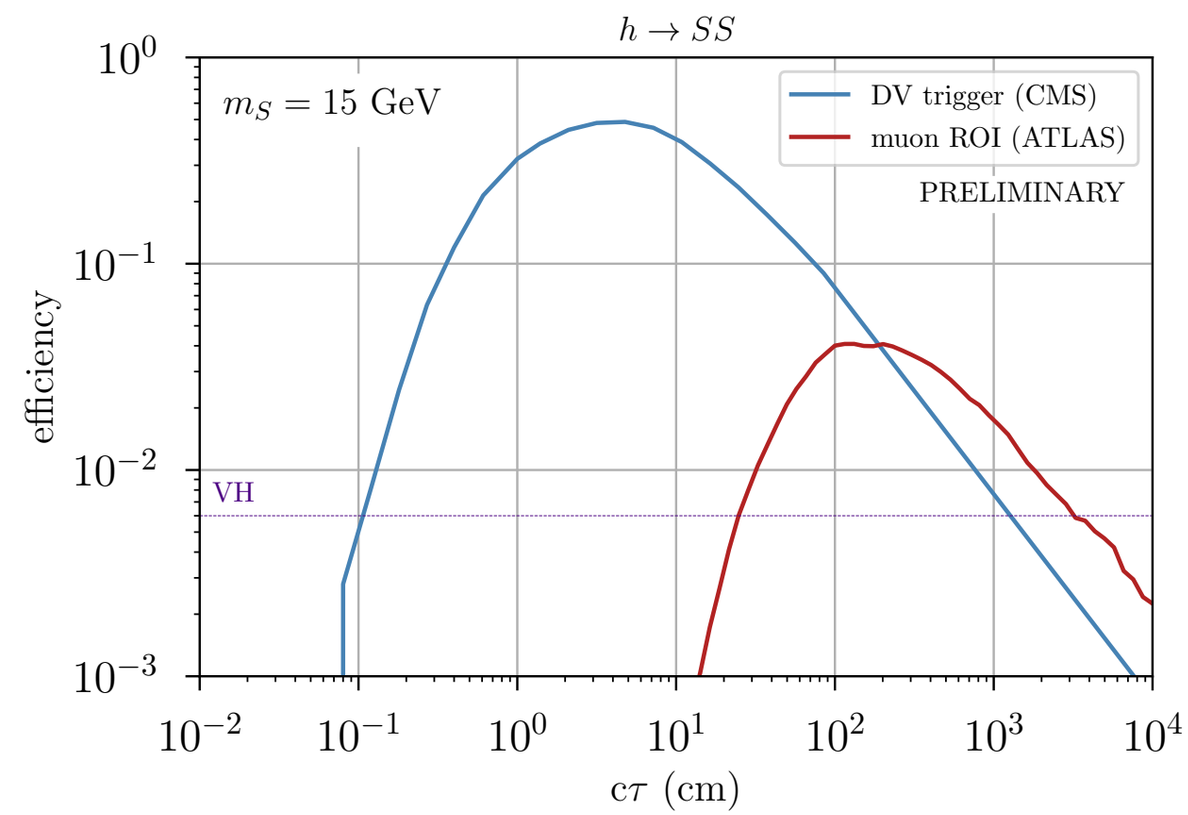
min track p_T	2 GeV	3 GeV	4 GeV
secondaries (kHz)	25	5	1
B-mesons (kHz)	0.13	0.04	0.01
fake vertices (kHz)	0.04	0.01	0.004

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

Results

Example: $h \to SS$
$\hookrightarrow$ hadrons





Qualitative gain in sensitivity appears possible

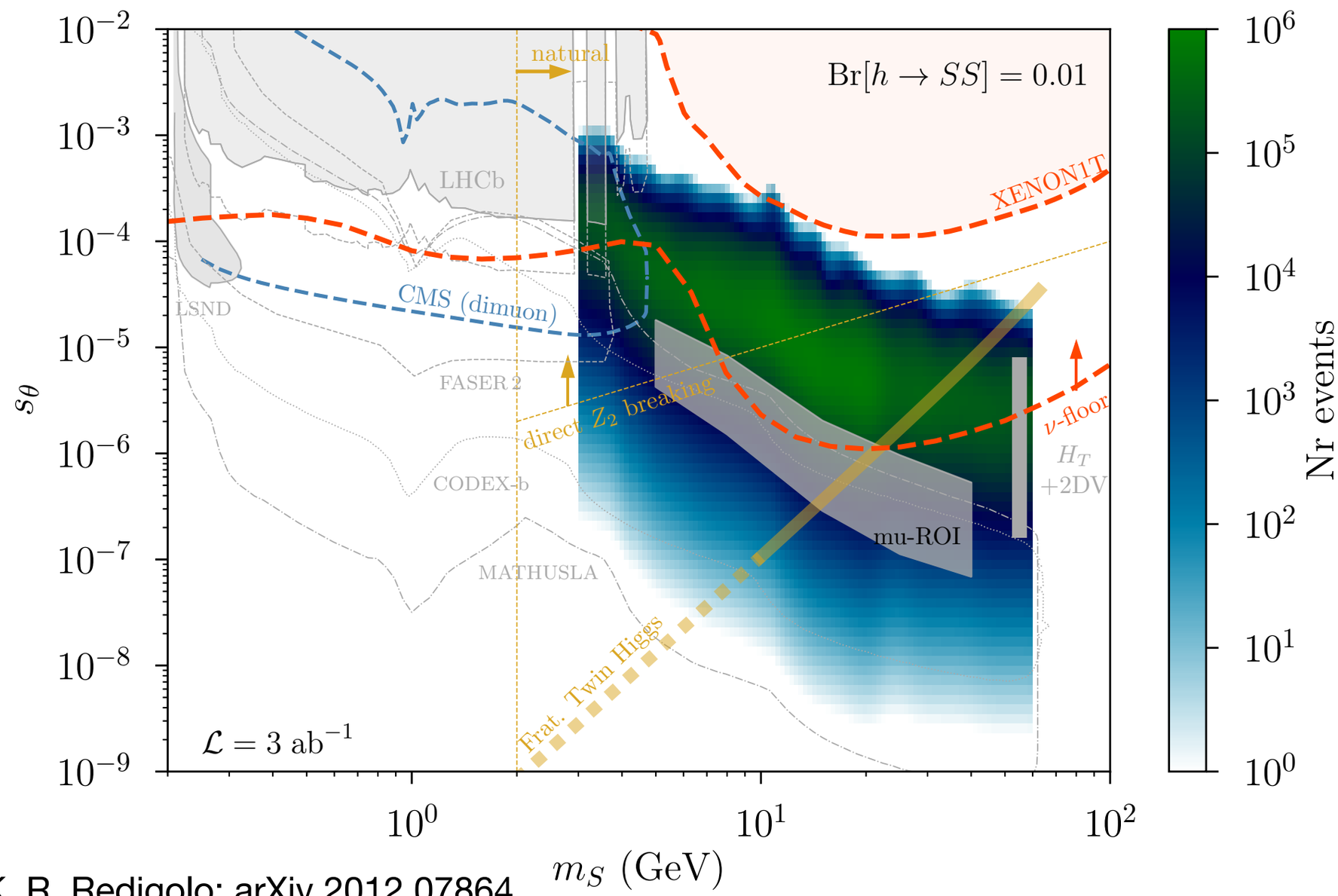
Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864
ATLAS muon ROI trigger: arXiv 1811.07370

Results

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

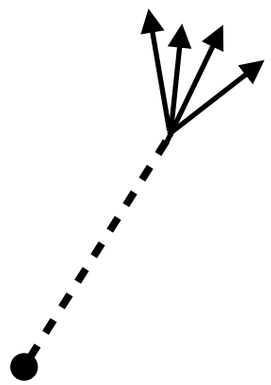
$h \to SS$

$\hookrightarrow$ hadrons



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

Things to do with the phase II upgrade



Displaced vertex triggers

(Higgs & B decays)

CODEX-b

CODEX-b experiment

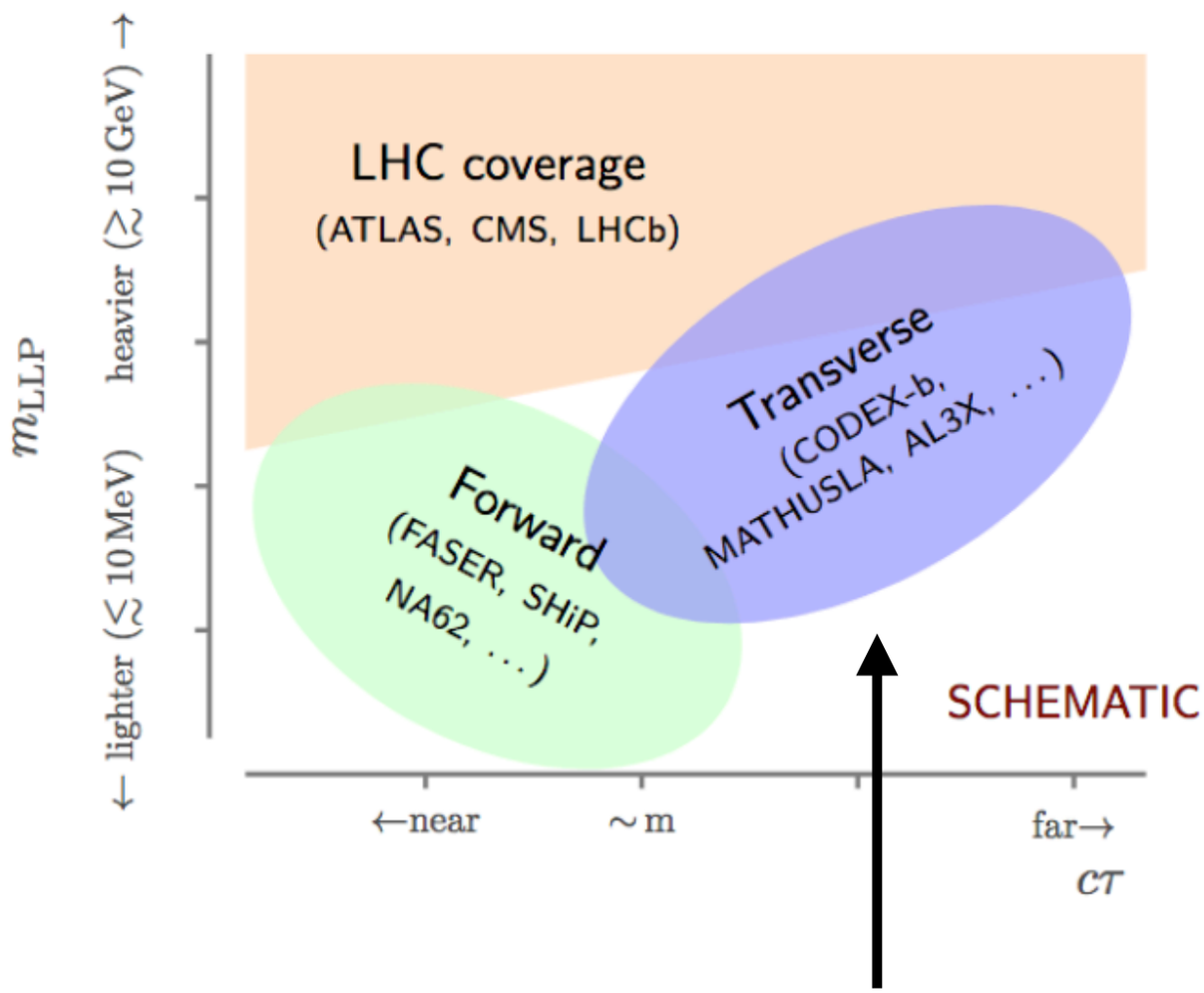
(Higgs & B decays)

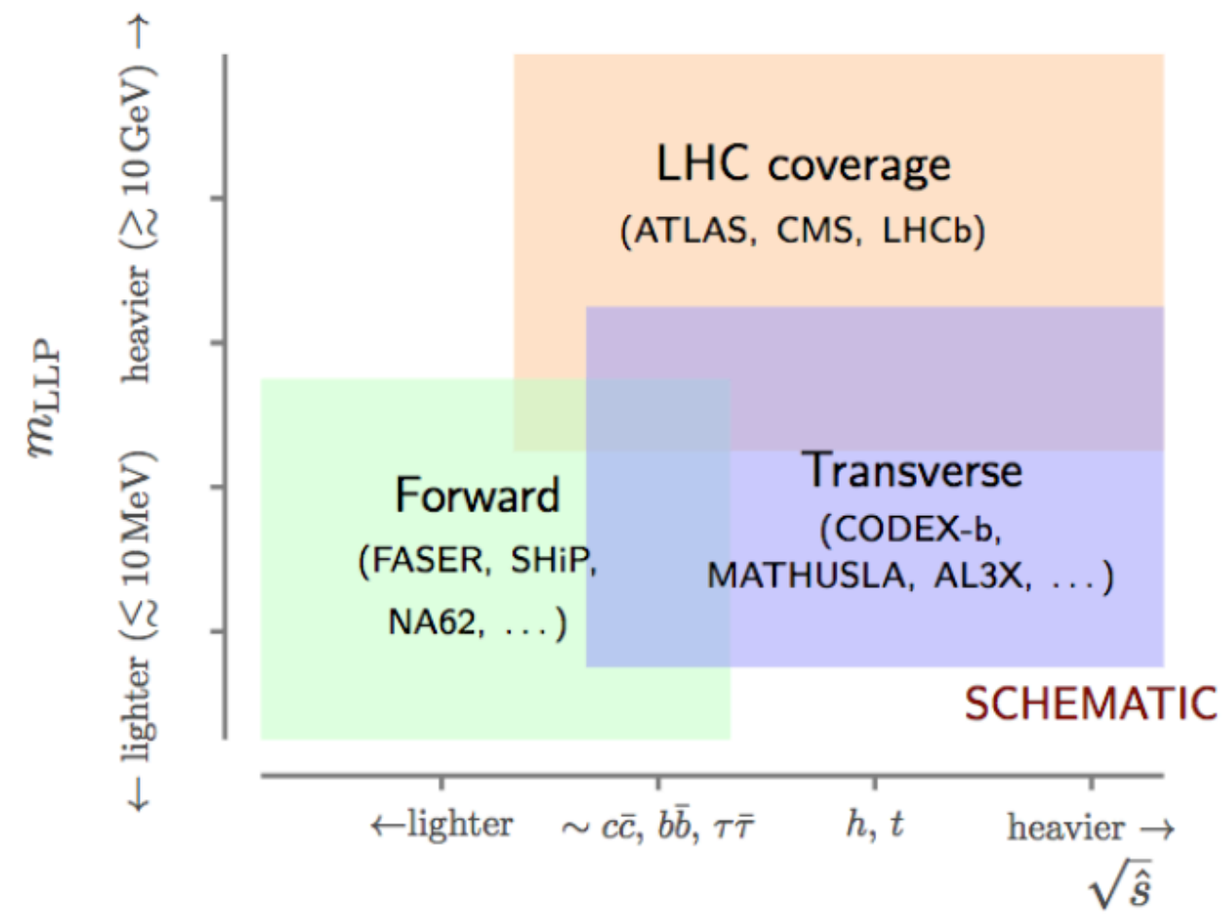
For particles with very long lifetimes, trigger and background challenges cannot always be overcome

↓

Need an external detector, shielded by a very thick hadron absorber

Why an external detector for long-lived particles?



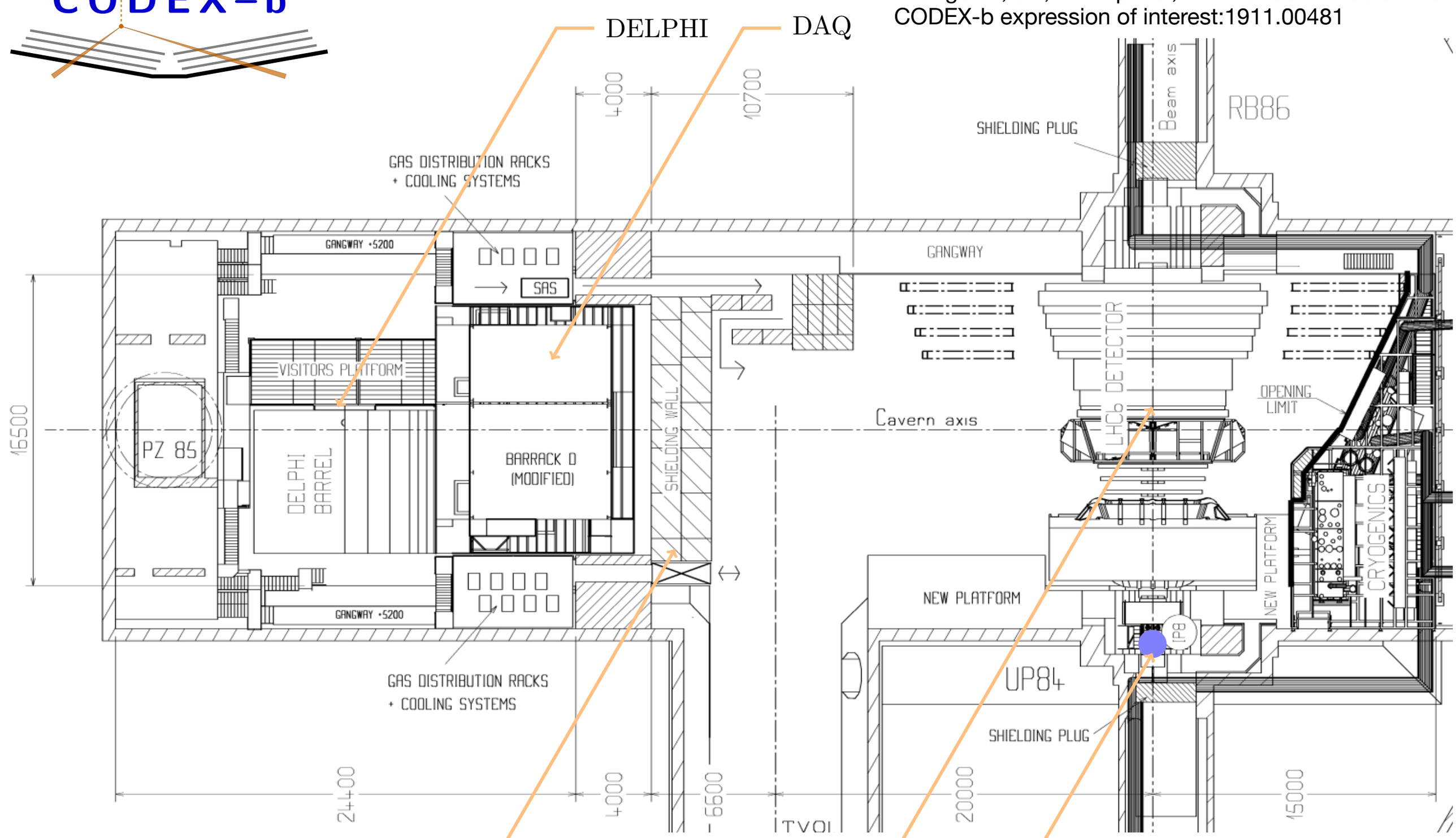


- Low mass
- High cτ
- Medium center of mass

This is where exotic Higgs & B decays live!

CODEX-b

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243
CODEX-b expression of interest:1911.00481

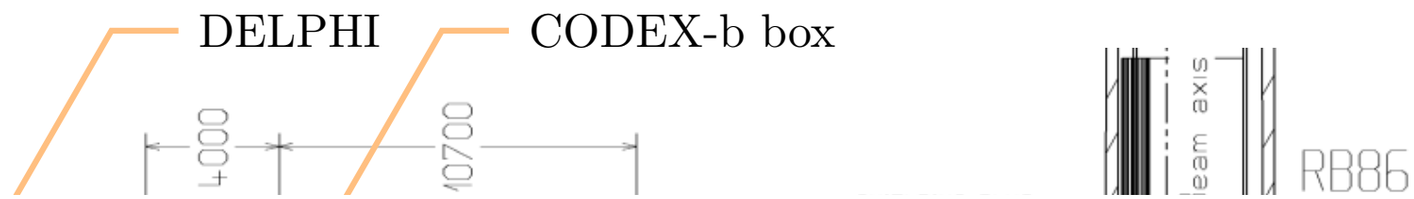


UXA shield — LHCb — IP8

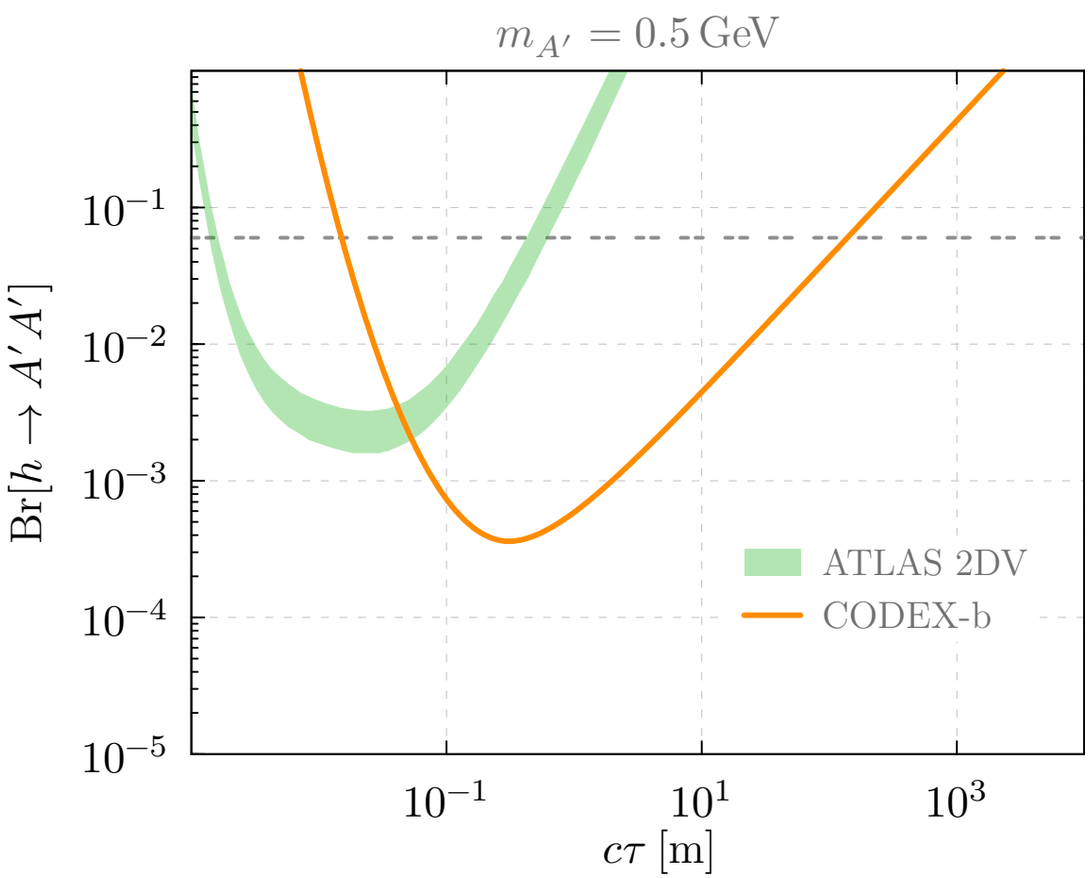
Data acquisition is being moved to surface for run 3

CODEX-b

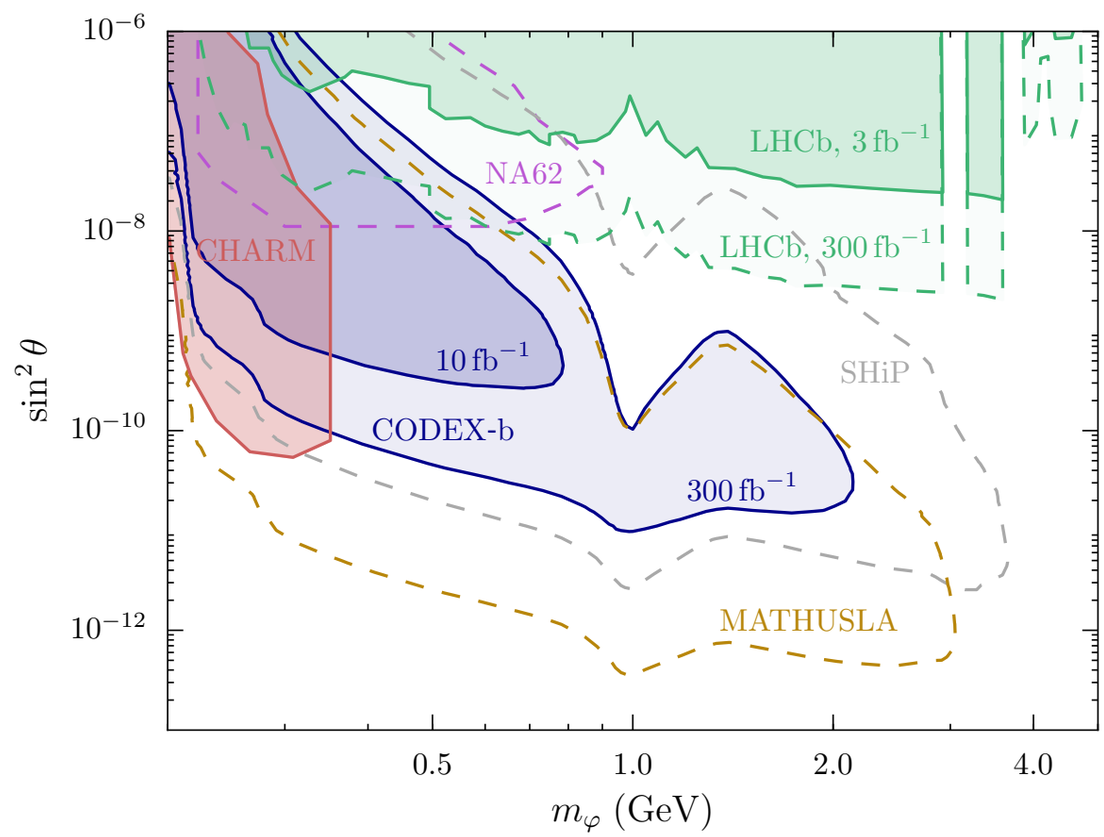
V. Gligorov, **SK**, M. Papucci, D. Robinson: 1708.02243

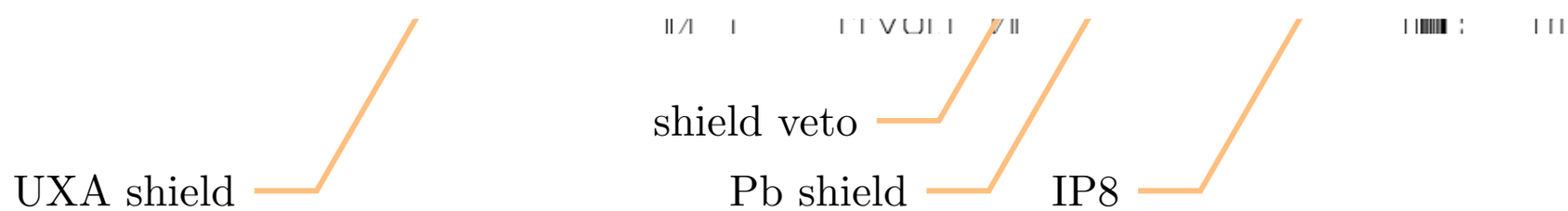


Exotic Higgs decays



Exotic B decays



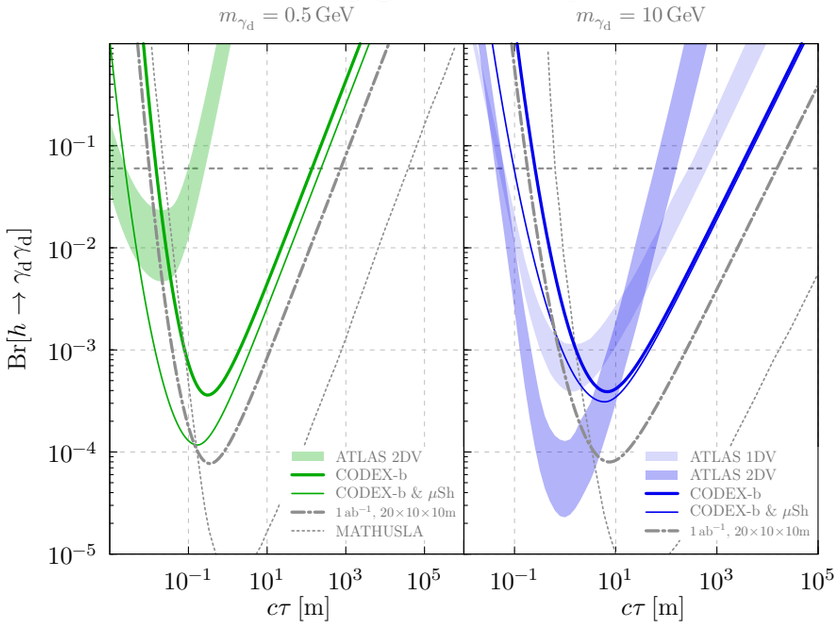


With ~ 4 meters of shielding, background free

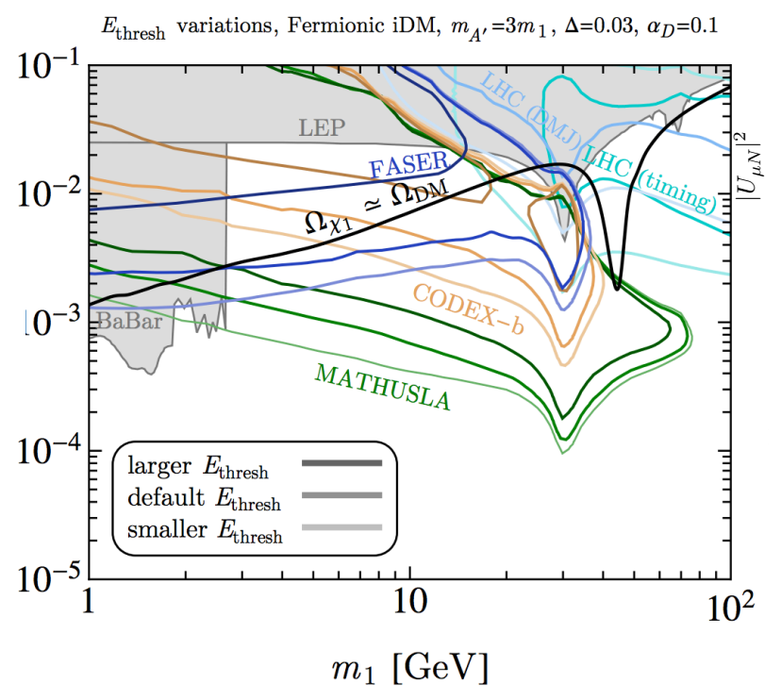
Other models

See CODEX-b "expression of interest": 1911.00481

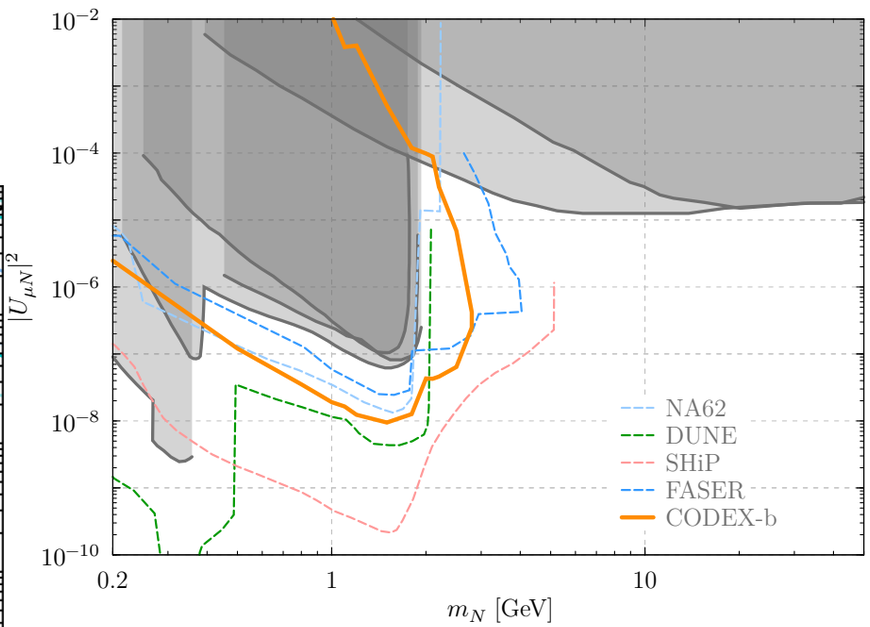
Higgs decays



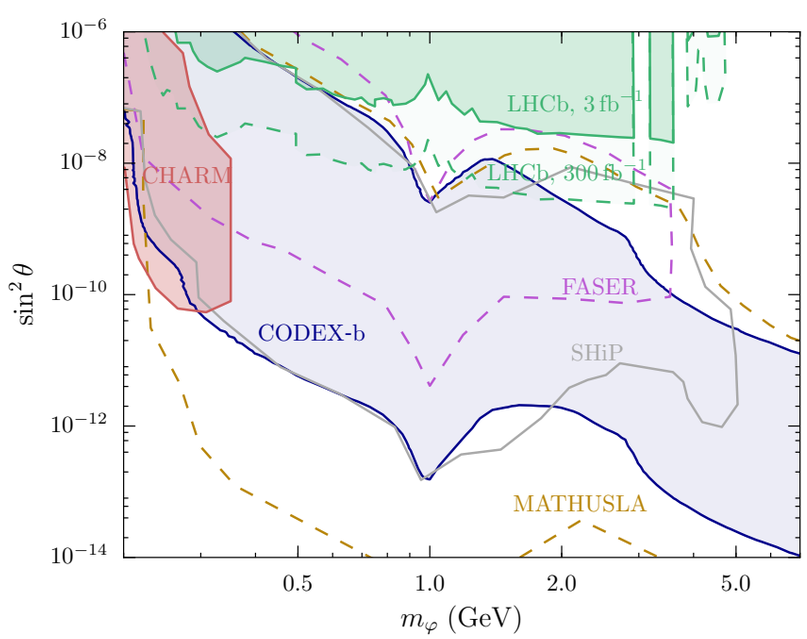
Inelastic dark matter

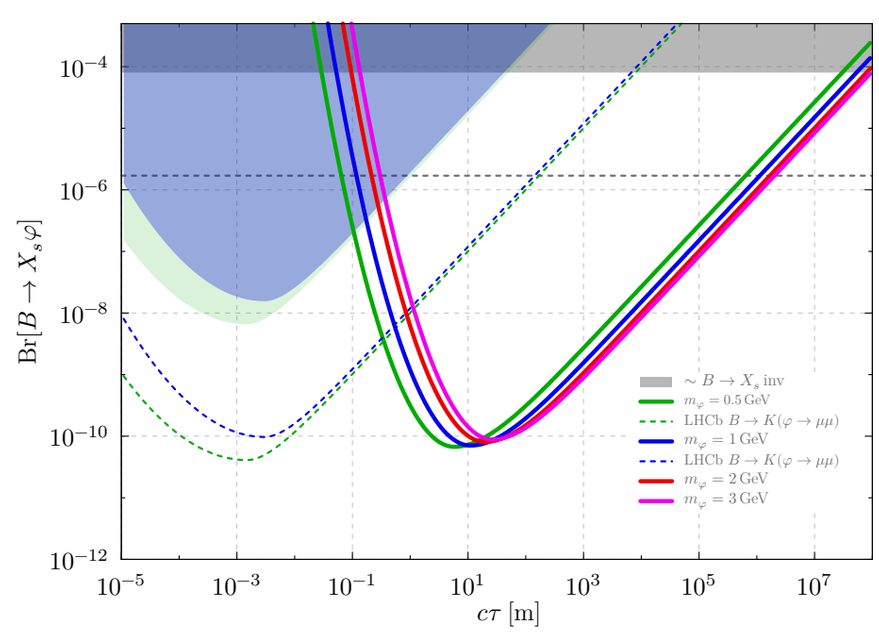


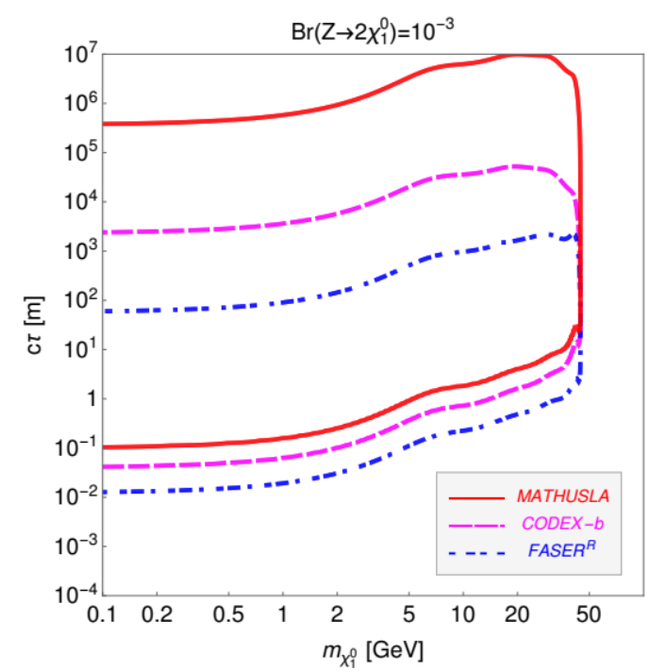
Heavy Neutral Leptons



More B decays

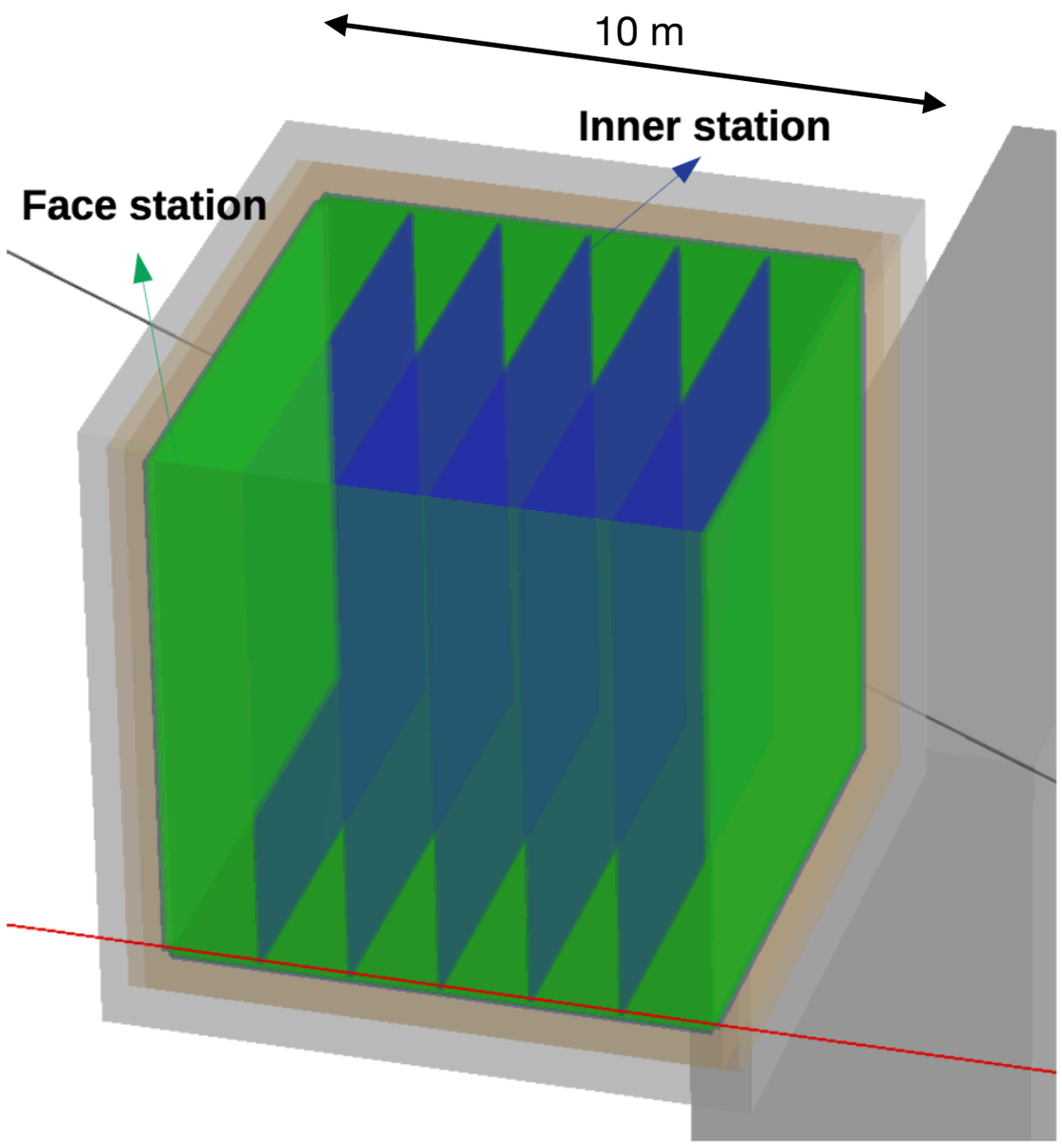






Z decays

Tentative detector design



Resistive Plate Chamber (RPC) panels

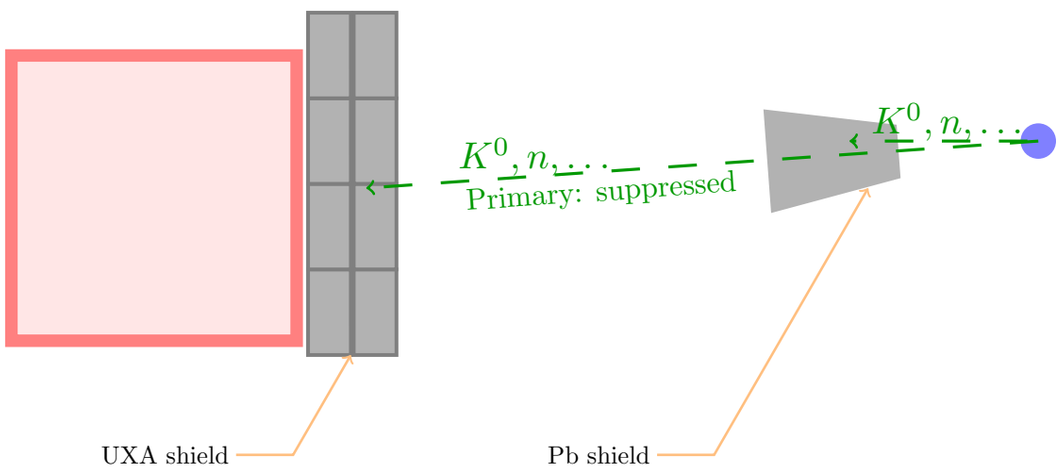
- Relatively cheap
- Large surface area possible
  (e.g. ATLAS/CMS, ARGO, MATHUSLA, …)

Fully integrated in LHCb trigger and reconstruction streams

Design drivers:

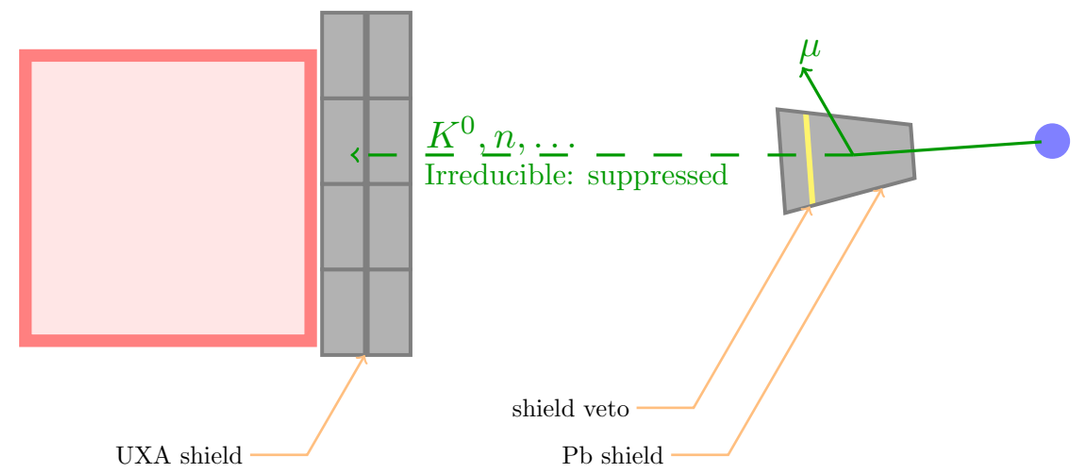
- Faces stations: recover acceptance for particles with low boost
- Inner stations: minimize distance to first tracked point

Backgrounds: hadron absorber



Neutral particles punching through the shield

Rate is small, but flux is large (!)



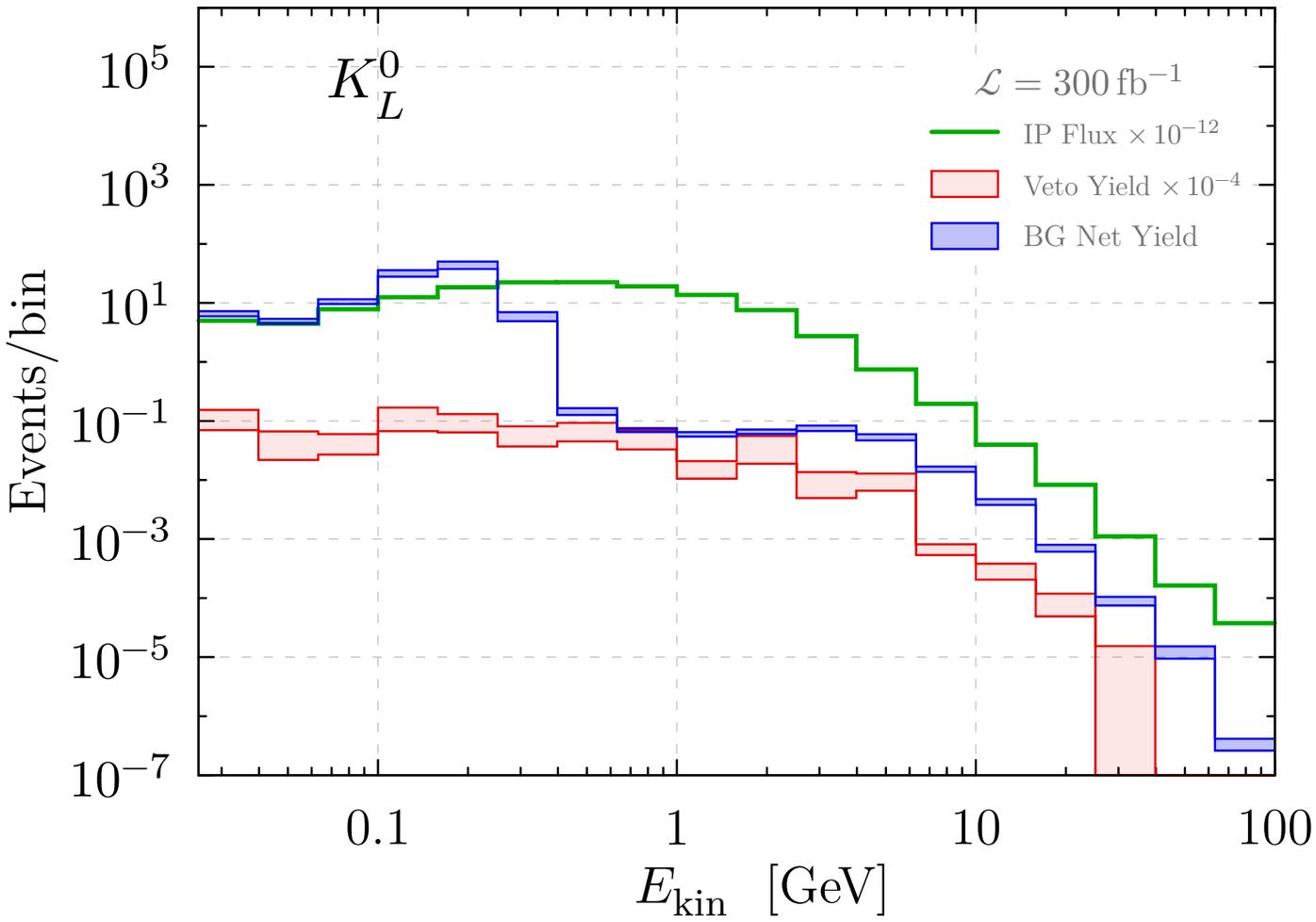
Neutral particles produced in the shield

Mostly from muons

Muon veto *in middle of shield* is critical

Backgrounds: hadron absorber

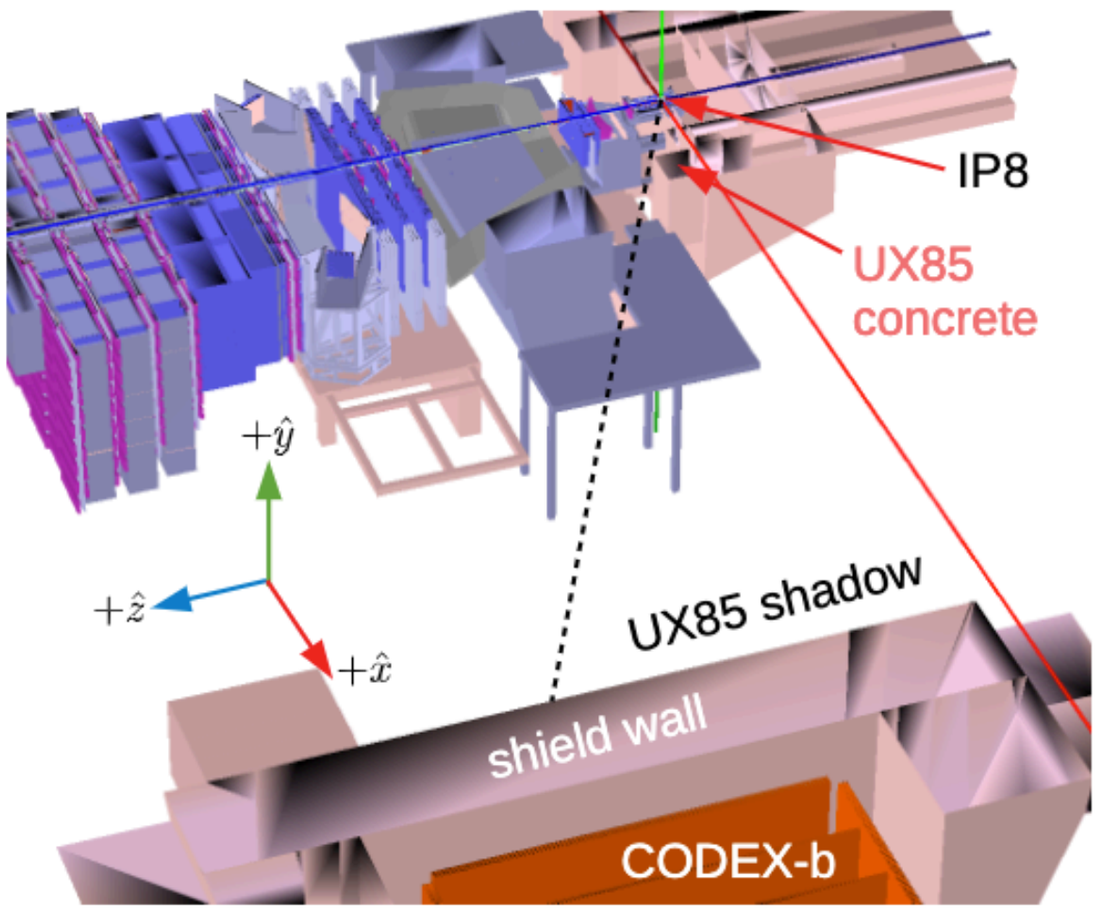
Example:

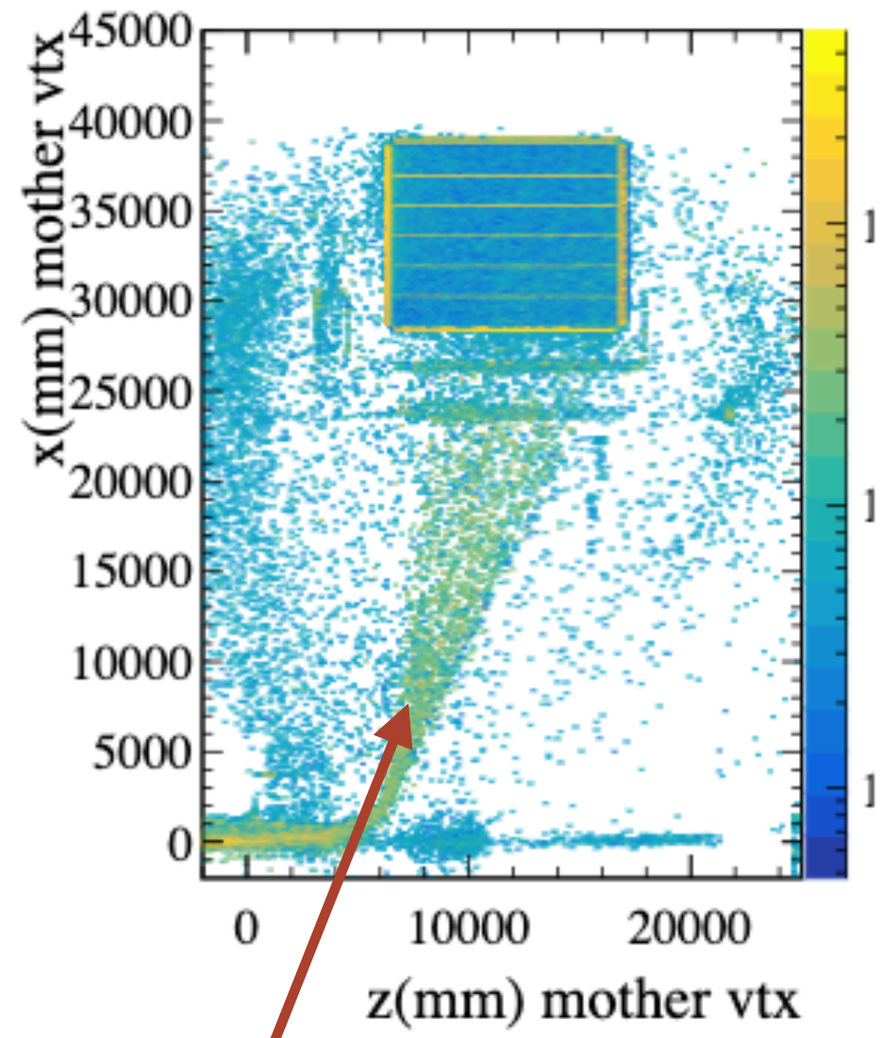


Backgrounds fully suppressed for ~ 4.5 m of shielding (Pb)

Backgrounds: Cavern

Soft particles swept towards detector: concrete wall is important





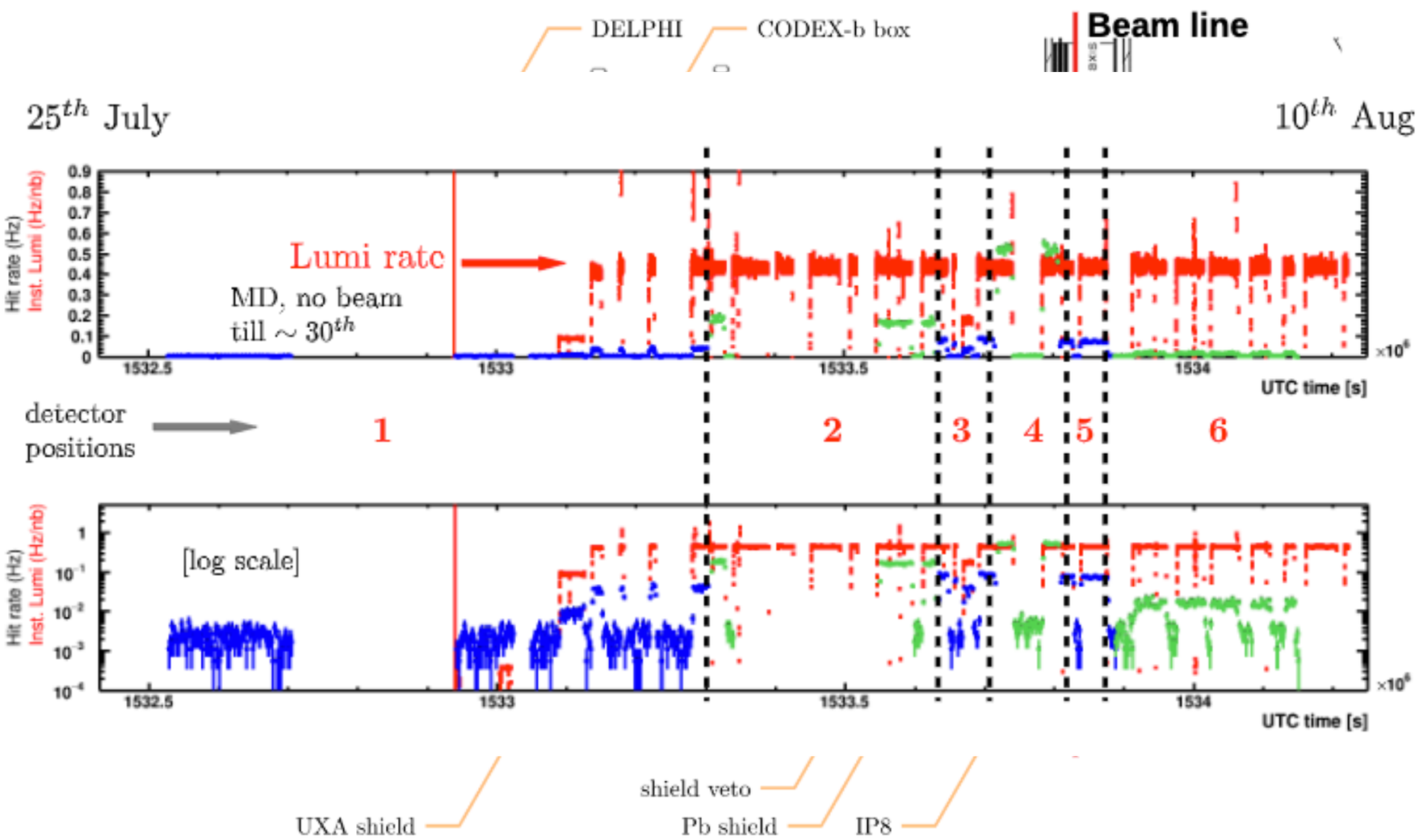
LHCb magnet

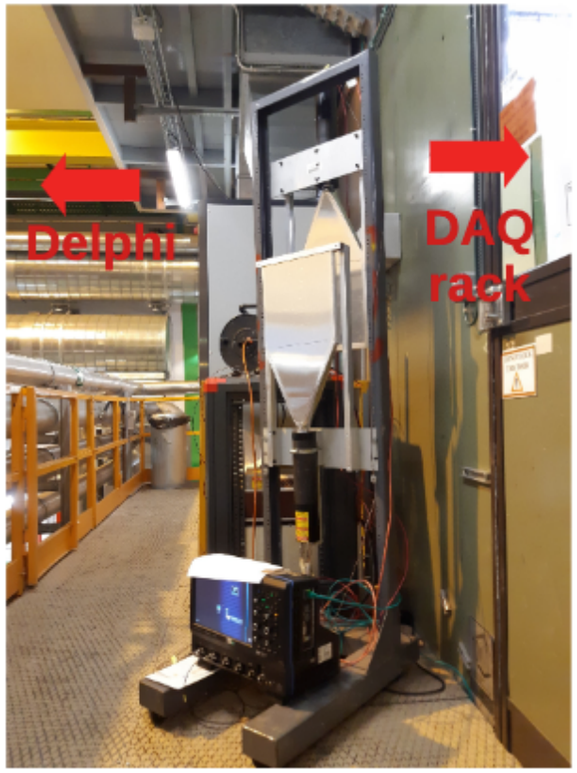
Important to understand detector noise and fake backgrounds

B. Dey et. al. :arXiv 1912.03846

Backgrounds: Measurement campaign

Muon data taken in various places in the cavern





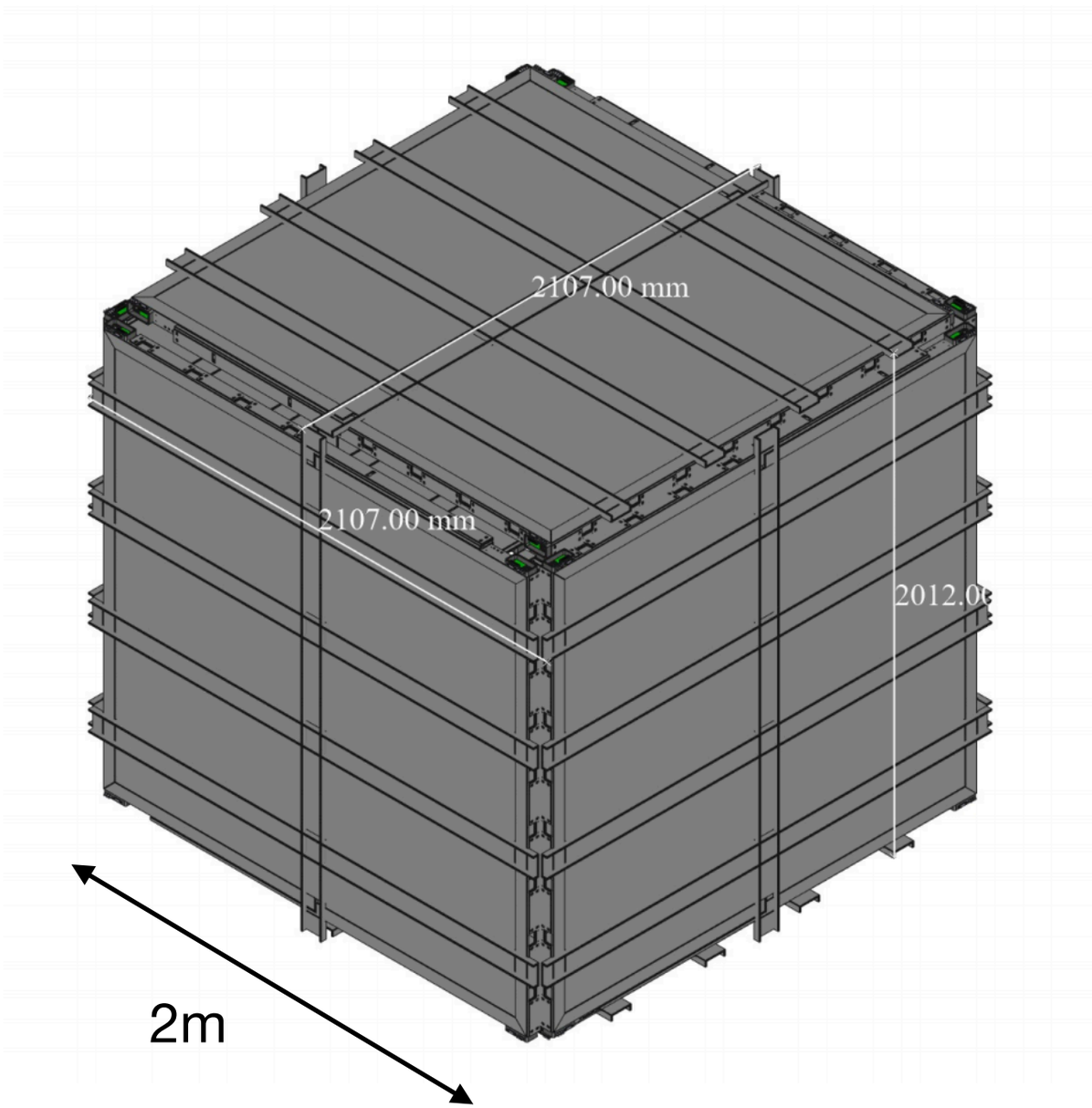
Good agreement with simulation and simulation is a bit conservative

B. Dey et. al. :arXiv 1912.03846

CODEX-β

FUNDED!

Demonstrator detector



Features

- Cube of resistive plate chambers (RPC's)
- Identical design to ATLAS muon chamber panels

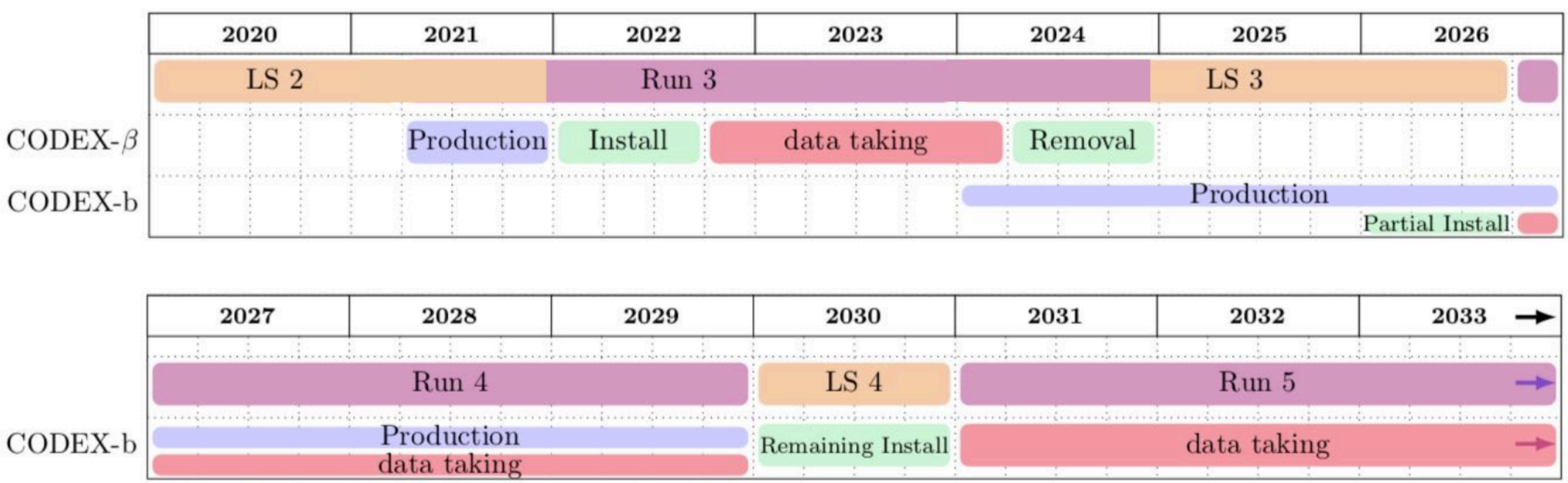
Goals

- Test event reconstruction strategy
- Measure background rate

Full detector would be roughly (10 m)^3

Status & outlook

- 30+ collaborators (ATLAS, CMS & LHCb)
- Completed “Expression of Interest”: arXiv 1911.00481
- Demonstrator detector design completed (CODEX-β)
- Planning for Letter of Intent and technical design report



Collaboration

CODEX-b

BERKELEY LAB

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

University of CINCINNATI

Duke UNIVERSITY

CERN

TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA Dipartimento di Fisica

INFN Sezione di Roma Tor Vergata

Eötvös Loránd University

UNIVERSITY OF BIRMINGHAM

LPNHE PARIS

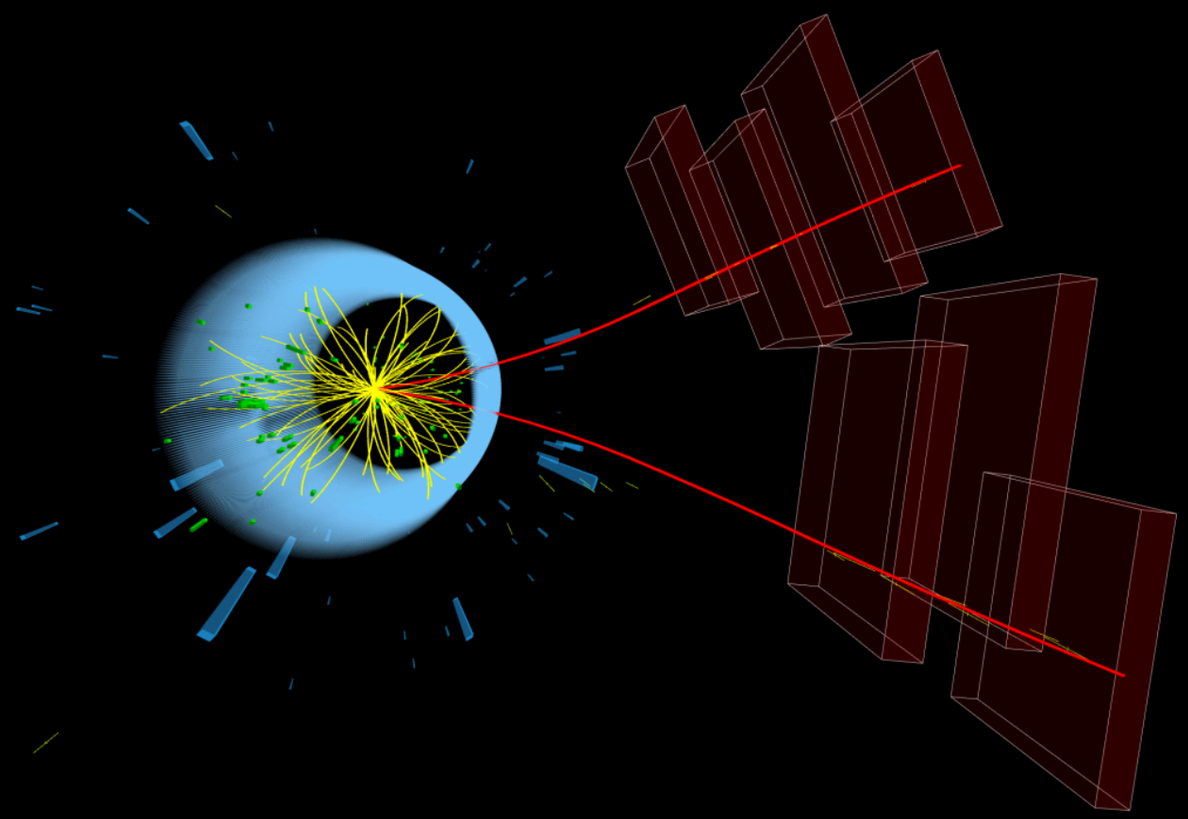
cnrs

erc

35+ members & growing

For a video tour: https://www.youtube.com/watch?v=V4Y7H_H2IKM

Conclusion



The LHC is a Higgs & B factory…

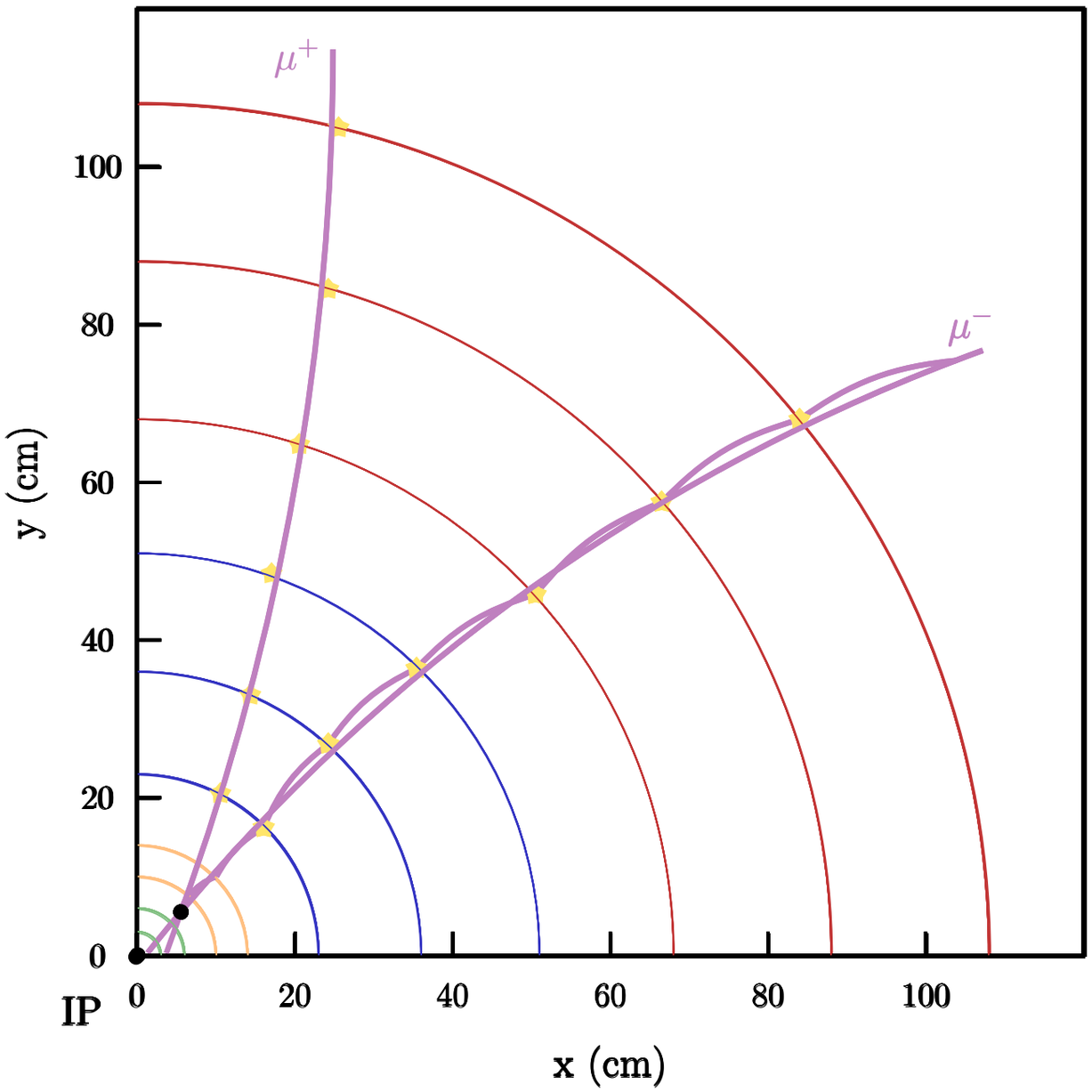
… Higgs and B decays are golden opportunities for beyond the Standard Model physics

New (trigger) strategies & dedicated detectors could yield qualitatively new reach…

… but we must be bold and continue to innovate!

Thank you!

Toy detector simulation

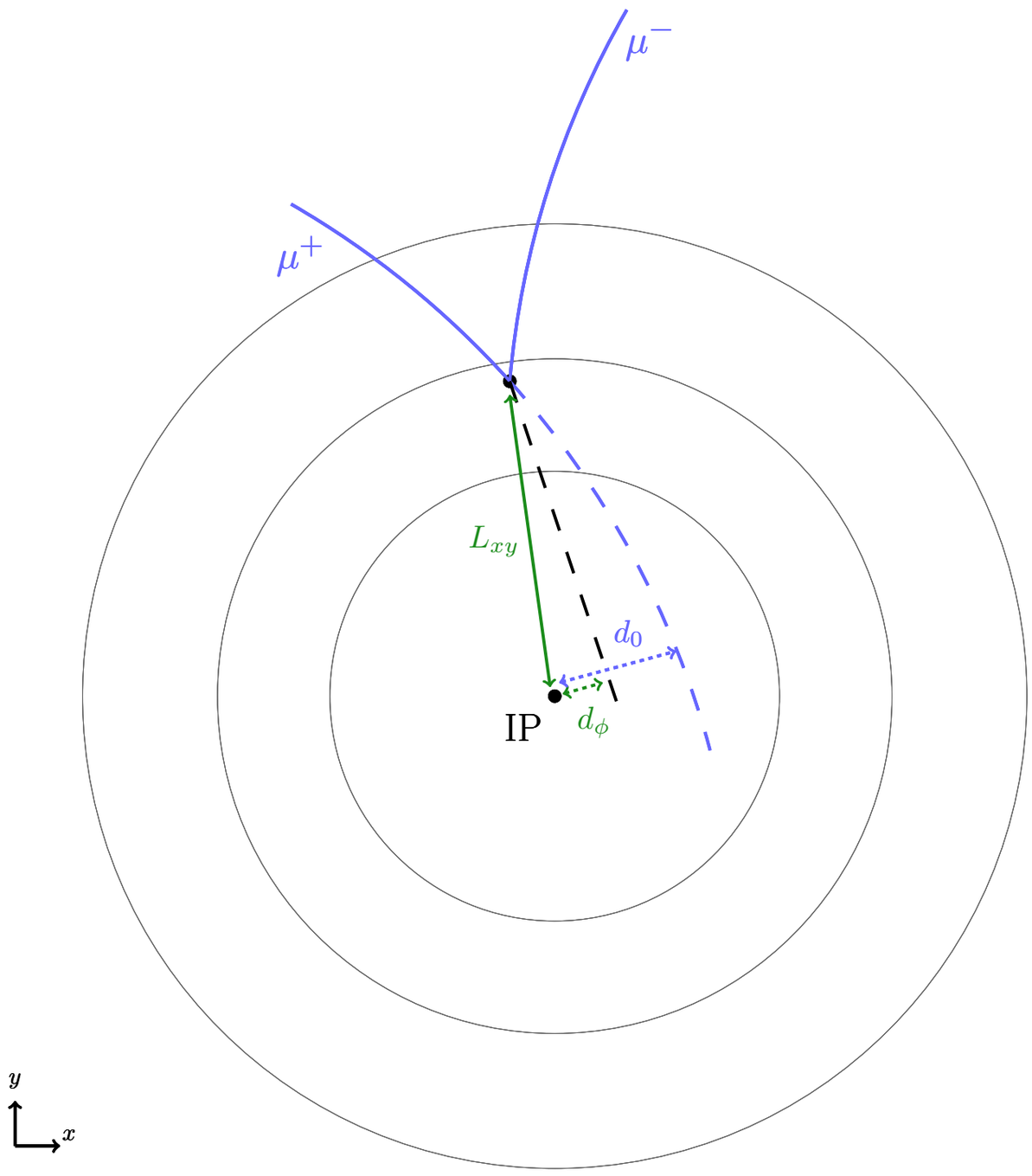


Procedure:

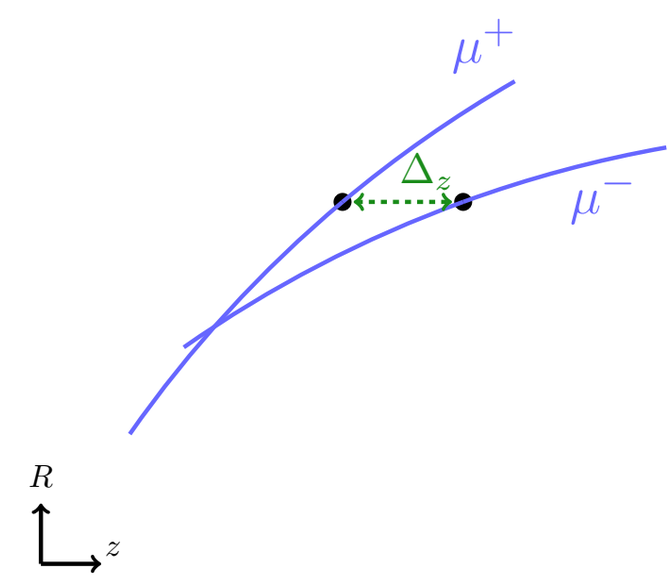
1. Propagate track
   (including multiple scattering)
2. Find the stubs
   (smearing for resolution)
3. Fit a helix to the stubs
   (require at least 5 stubs)
4. Reconstruct a vertex

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

Some notation



Vertex is never perfect:
Δ_z measures vertex quality

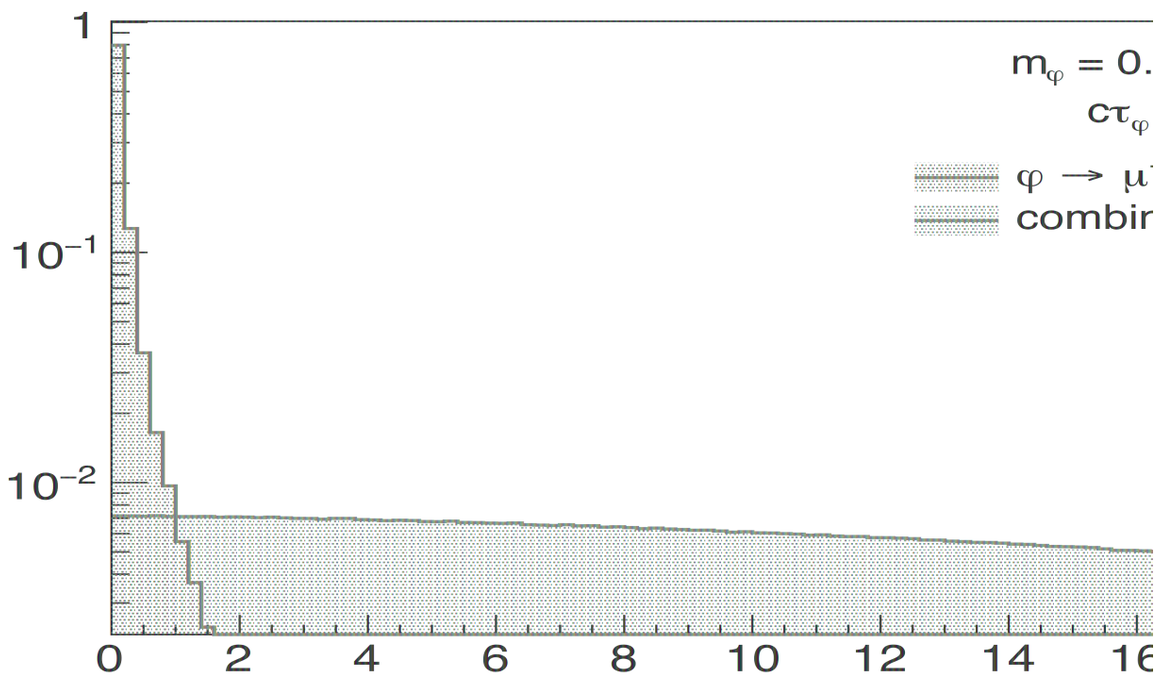


Y. Gershtein, SK: arXiv 1907.00007

Fighting fakes

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

Distance between tracks in z-direction

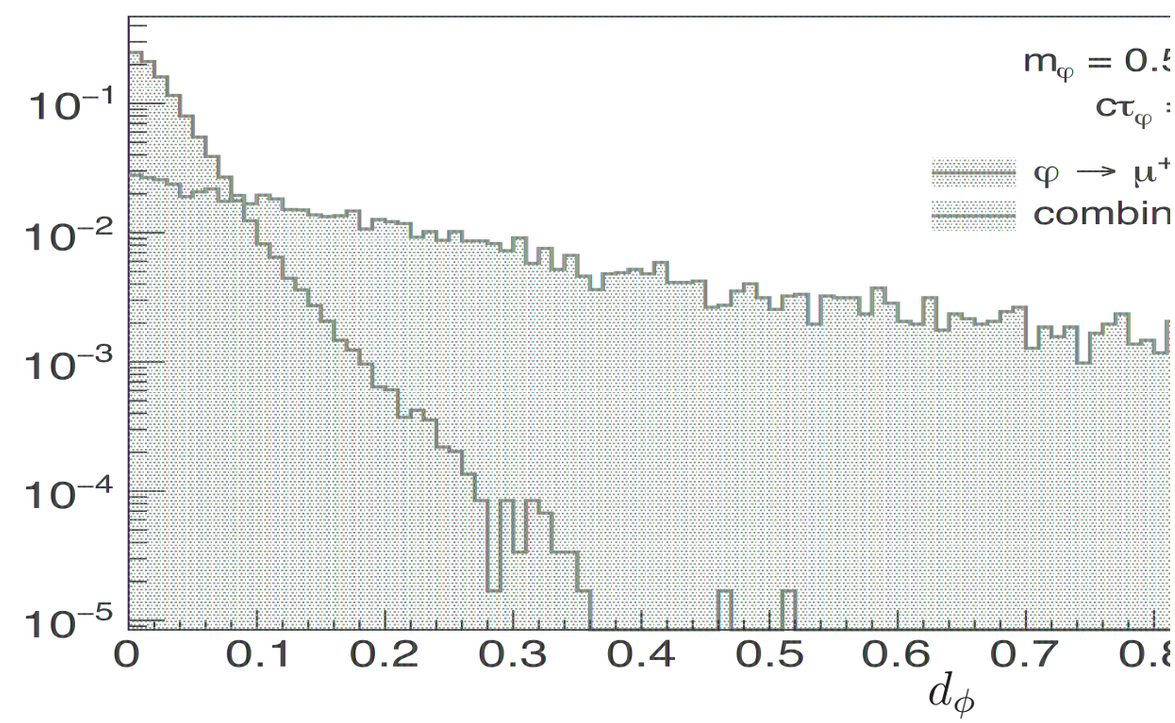


$\Delta_z < 1.0\,\mathrm{cm}$

↓

~ 10^{-2} suppression

Impact parameter of mother



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

↓

~ 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)

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

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

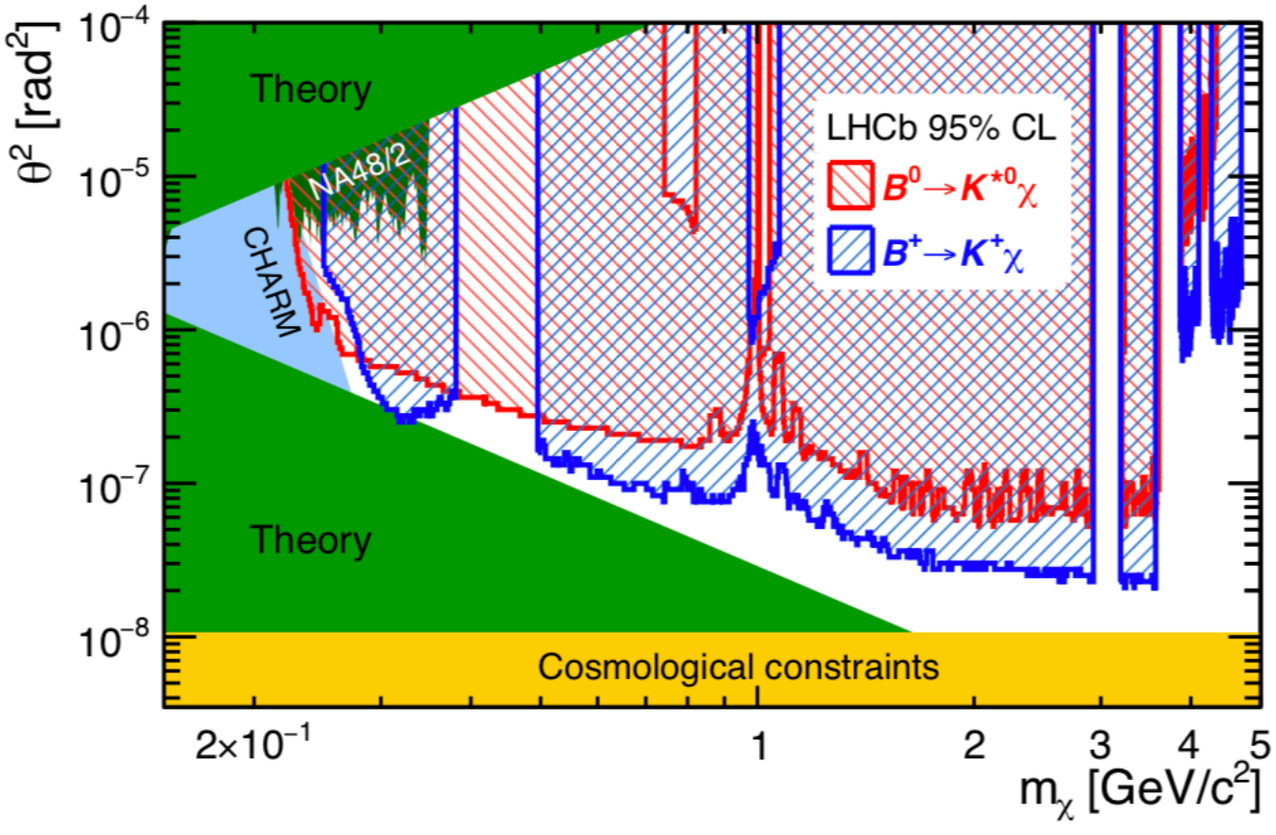
<u>3 lifetime bins:</u>

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

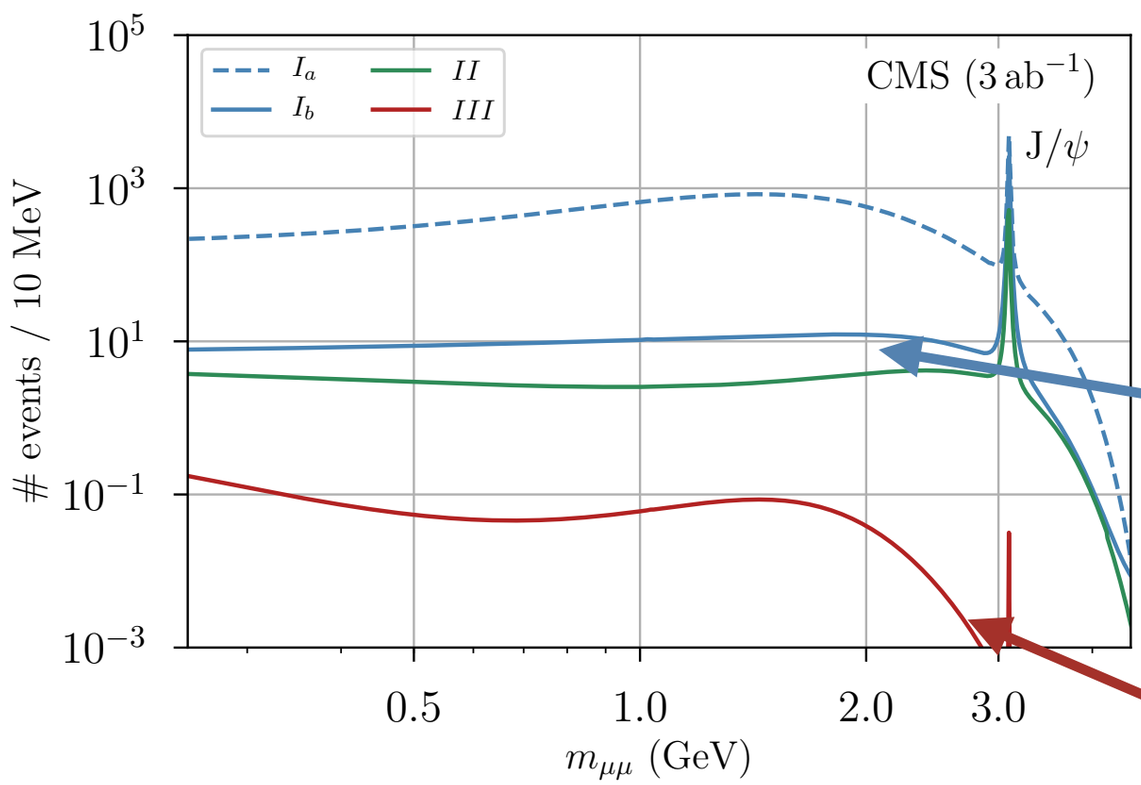


Offline analysis

Main background from B-meson decays

<u>For example:</u>

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



Can be reduced to O(1) levels with:

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

Additional cuts (next slide)

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

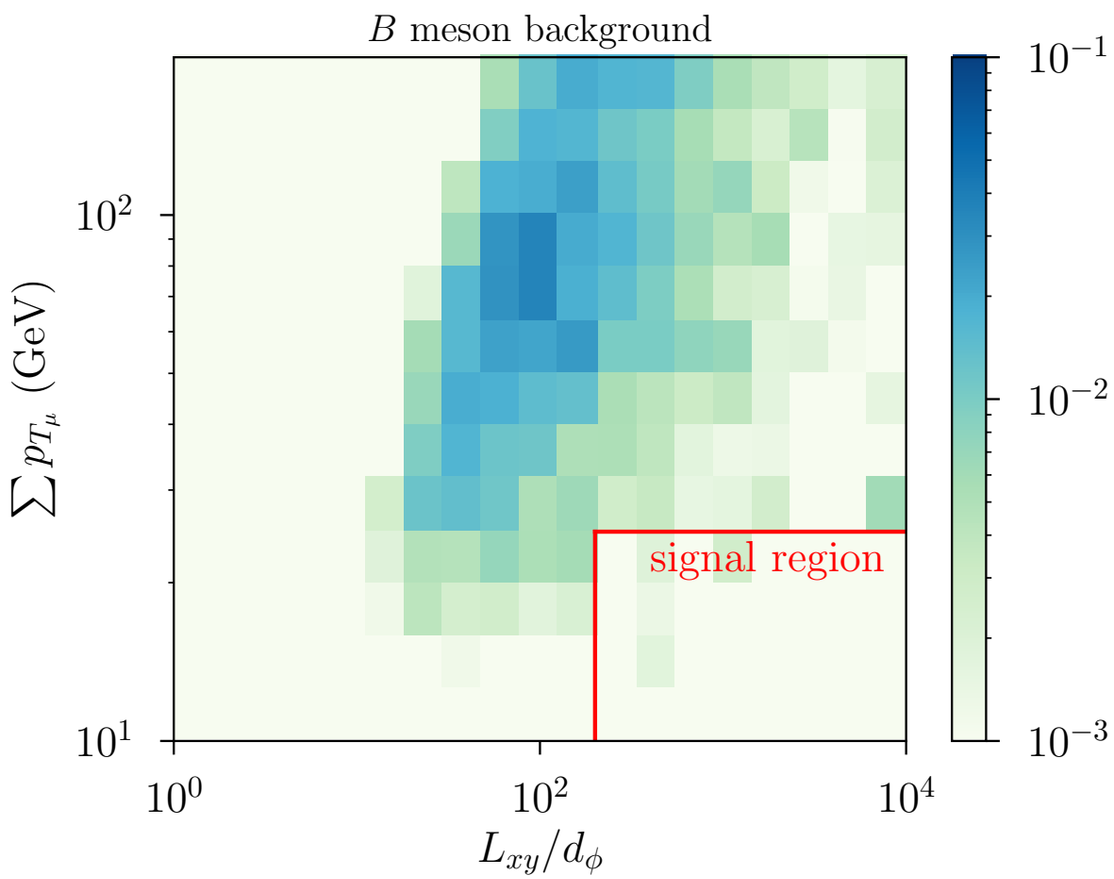
Additional cuts

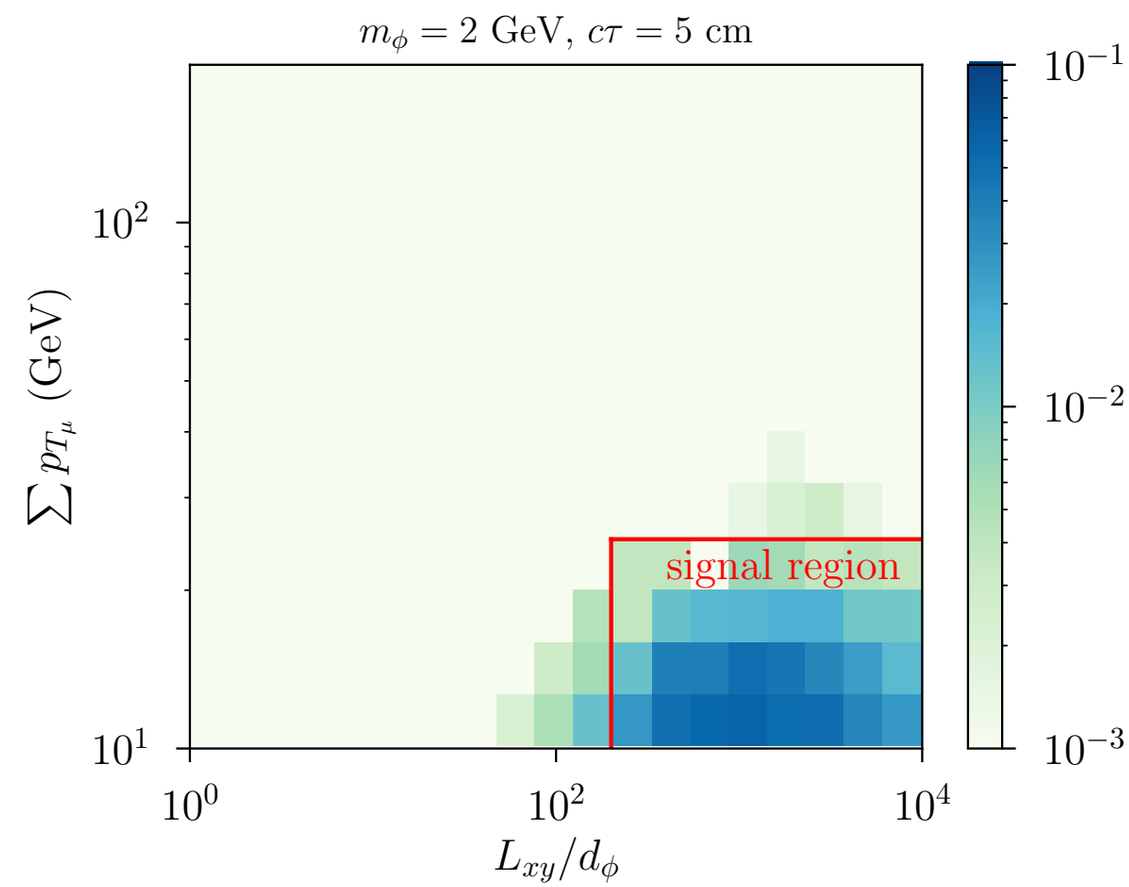
Main background from B-meson decays

<u>For example:</u>

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

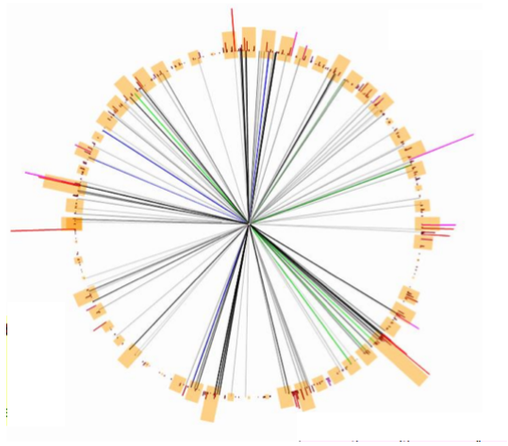
- Background passing the L_{xy} cut is high p_T
- Signal tends to point back to IP





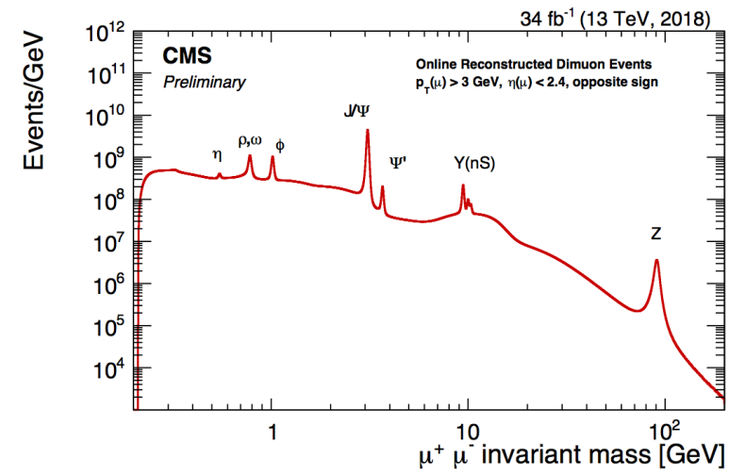
J. Evans, A. Gandrakota, SK, H. Routray: arXiv 2008.06918

Examples of things to do now



"Dark showers"

(Higgs decays)



Data scouting / Data parking

(B decays)

↓

Strongly coupled extensions of the Standard Model produce very exotic events

- Search of displaced vertices
- Machine learning techniques

↓

Scouting: record small fraction of the event
Parking: reconstruct event later

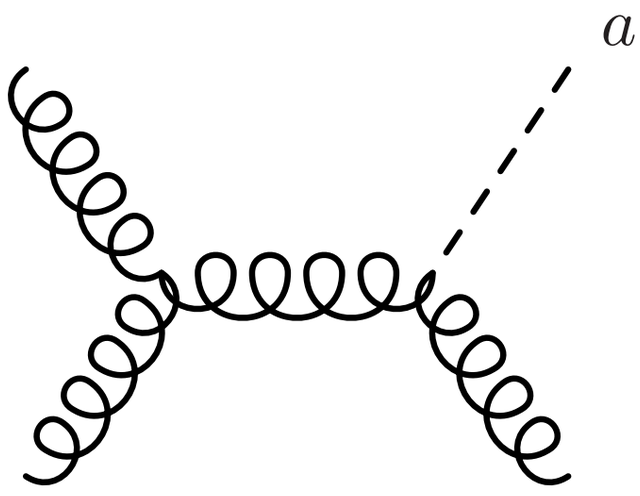
Allow to search of phenomena which would otherwise not pass the trigger thresholds

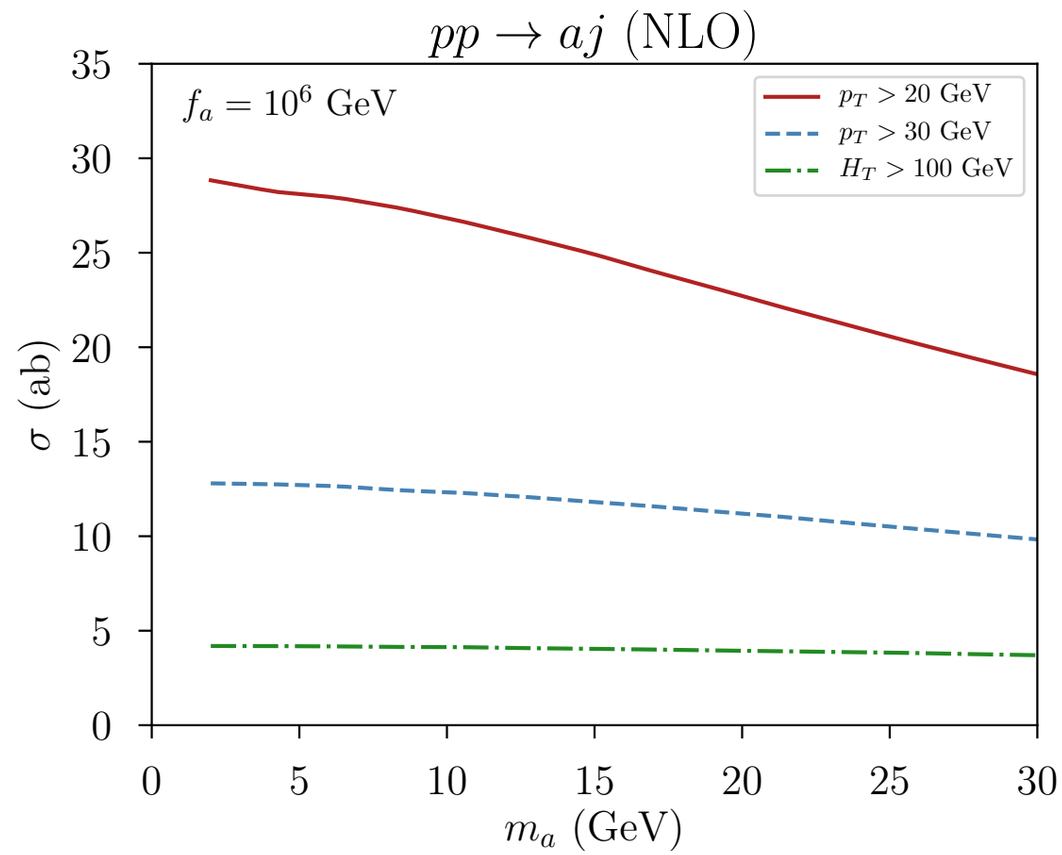
But plan must be in place *before* data taking!

Event display by Matt Strassler

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

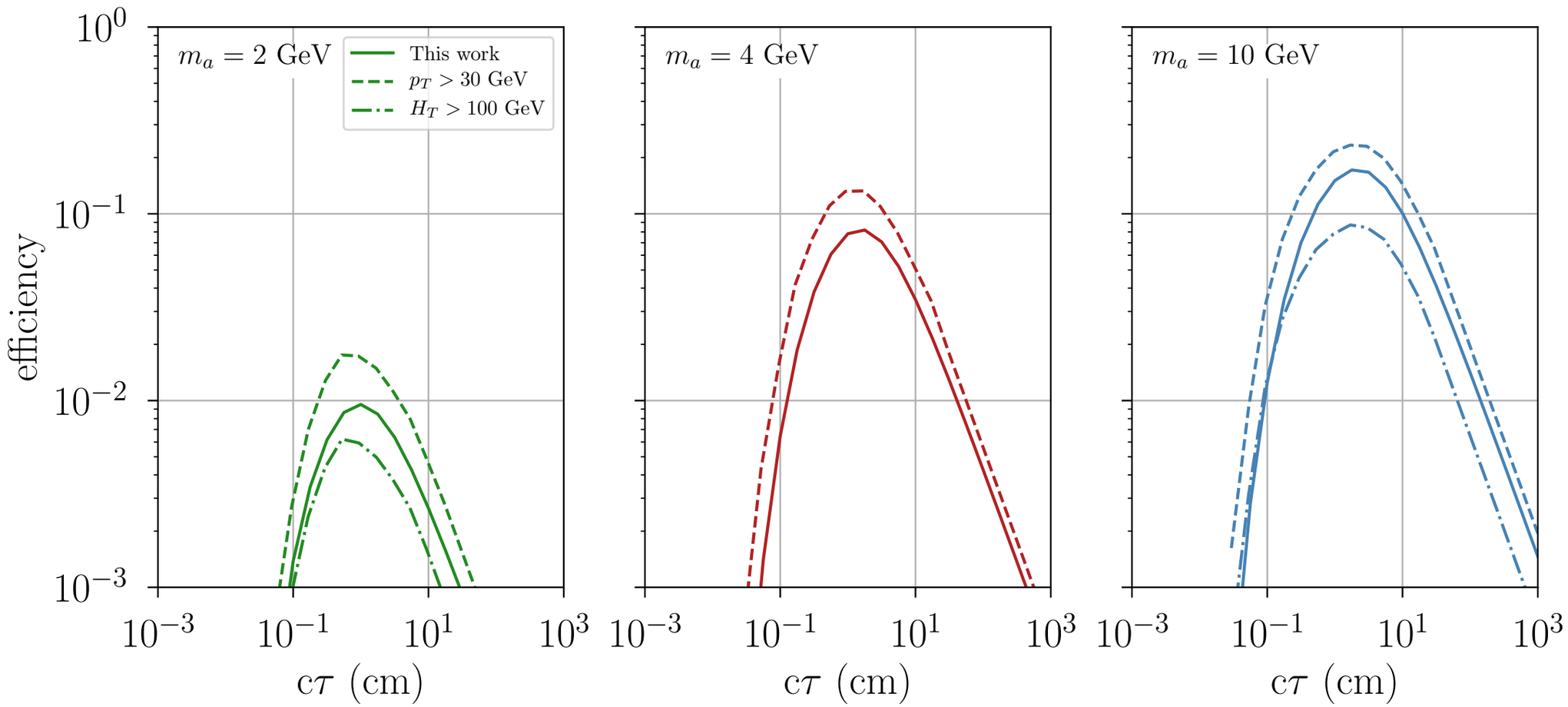
Lifetime:

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

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

Axion-like particle

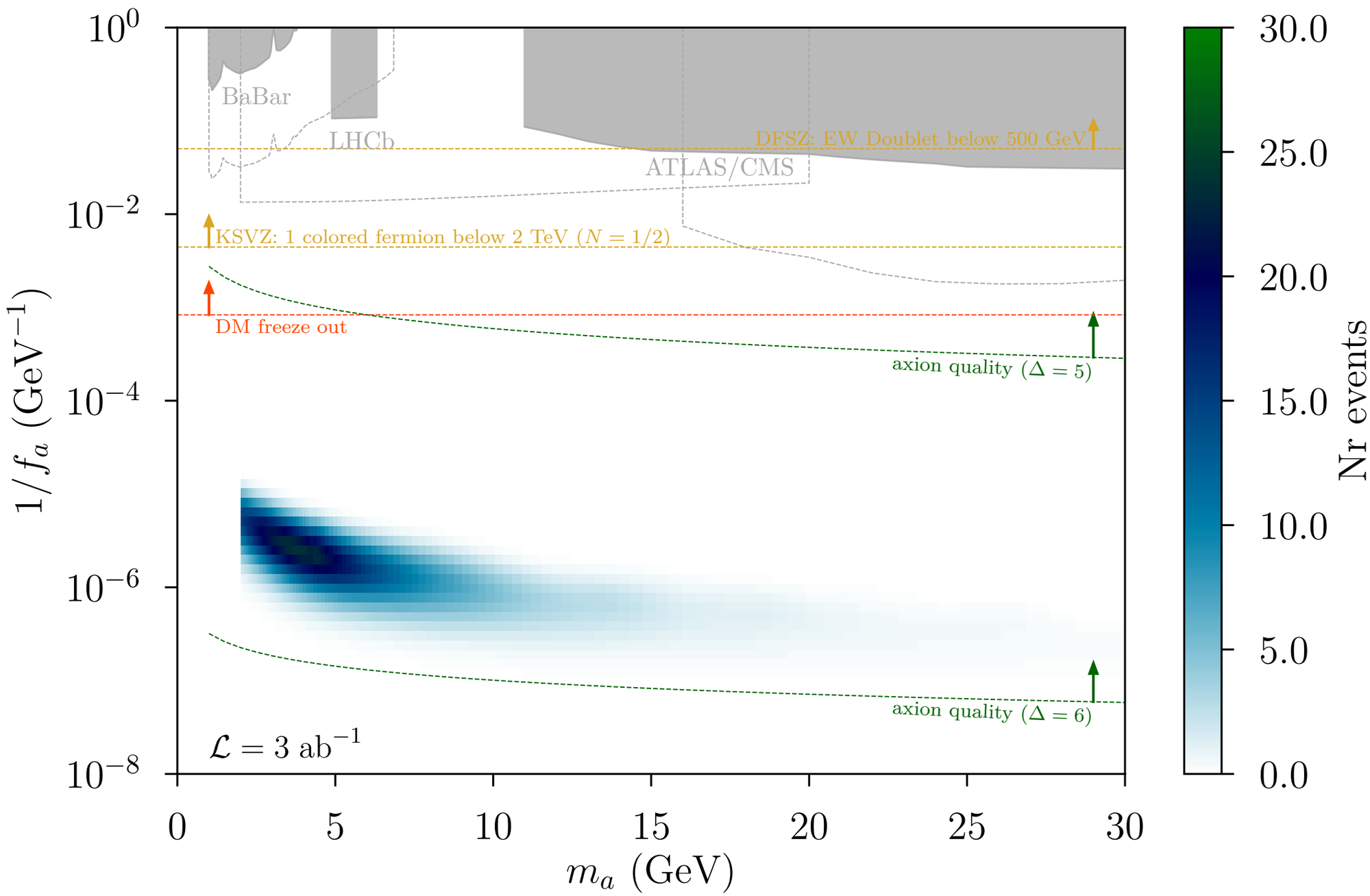
Efficiency:



Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864
See also: A. Hook, S. Kumar, Z. Liu, R. Sundrum: 1911.12364

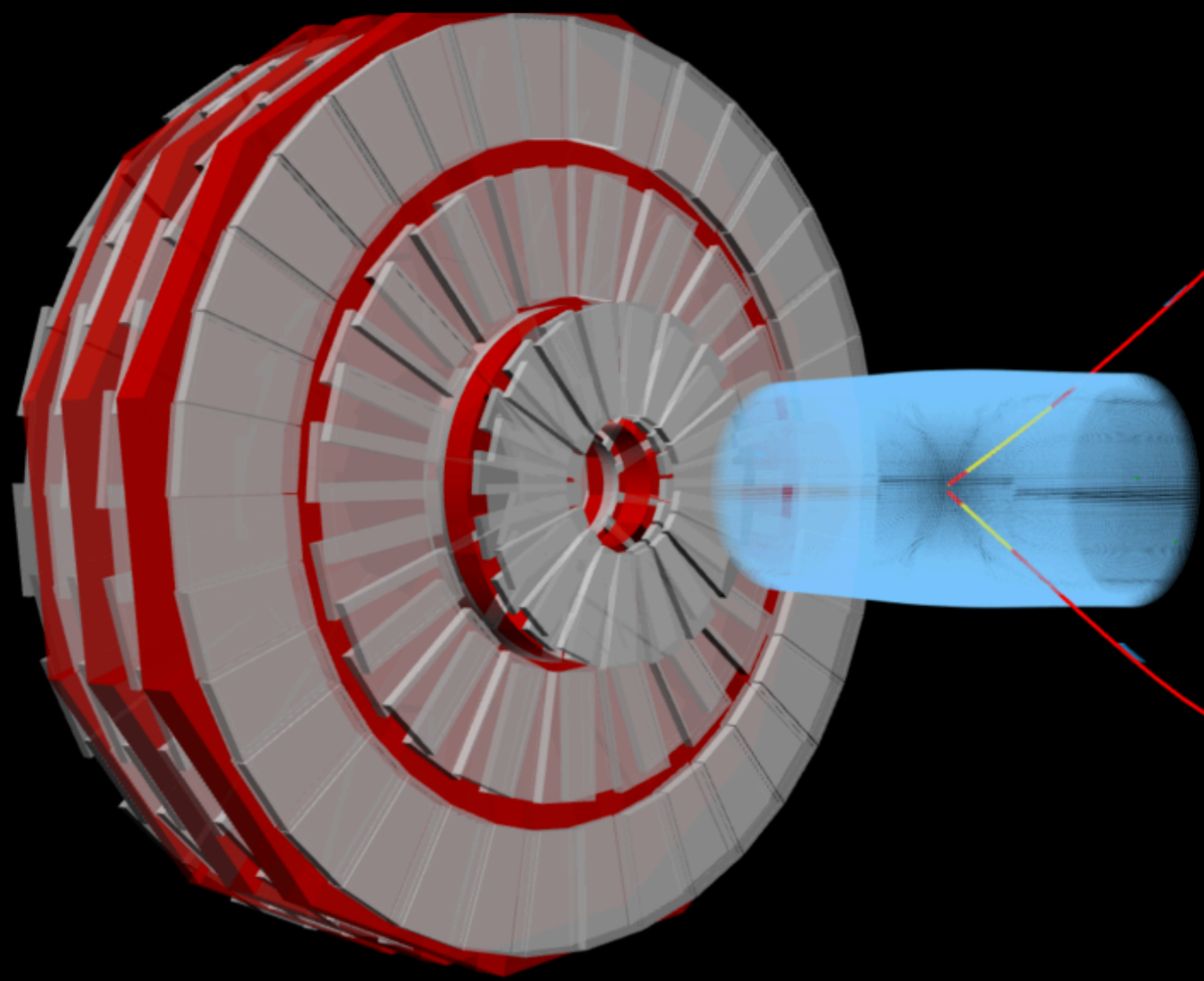
Axion-like particle

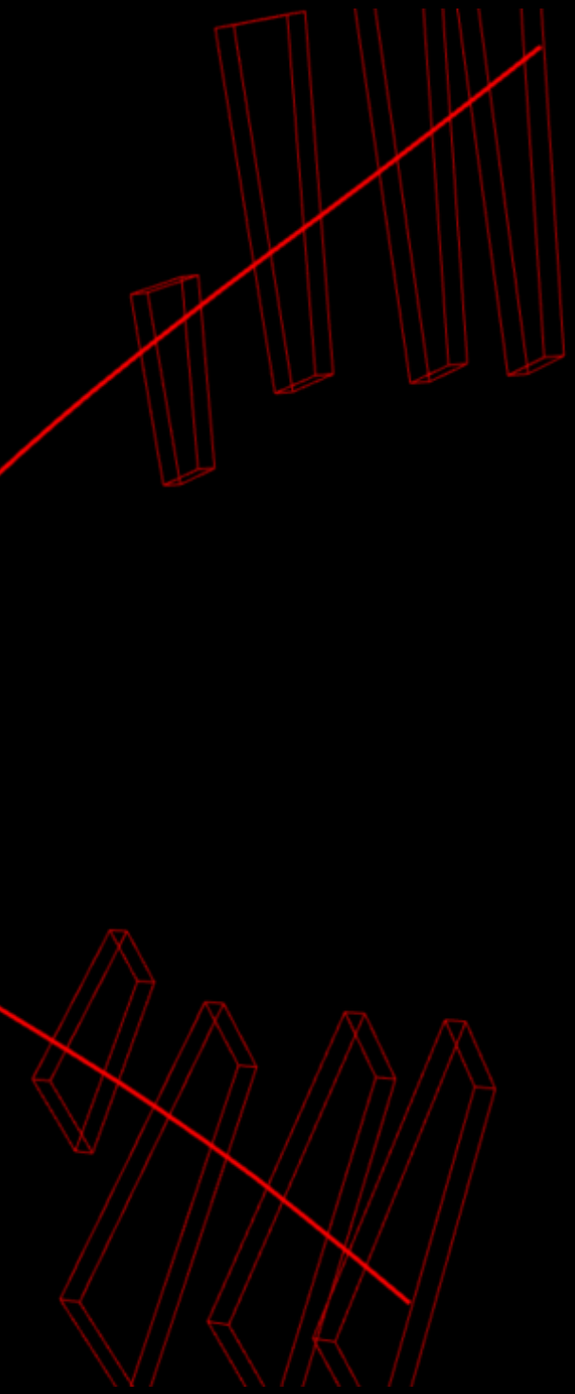
Result:

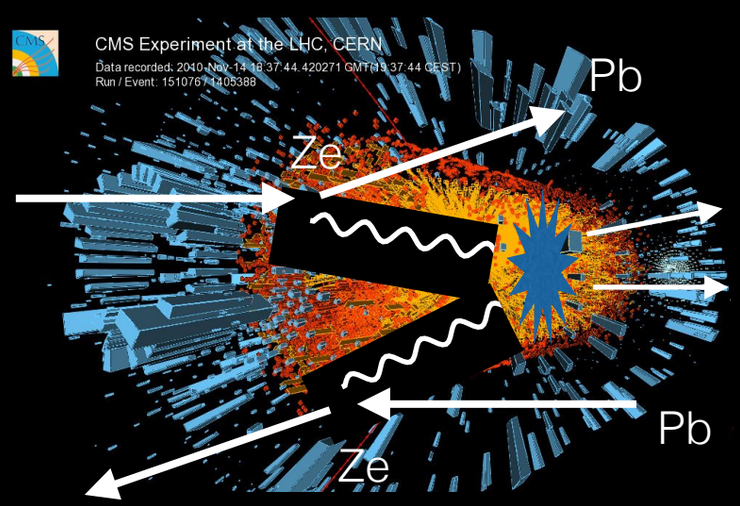


Y. Gerhstein, SK, R. Redigolo: arXiv 2012.07864

Ultra-peripheral collisions







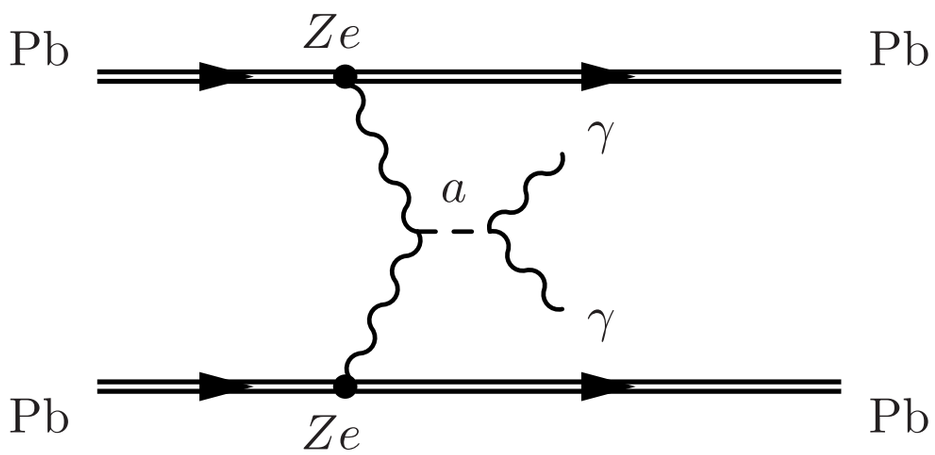
Head-on Pb-Pb collision

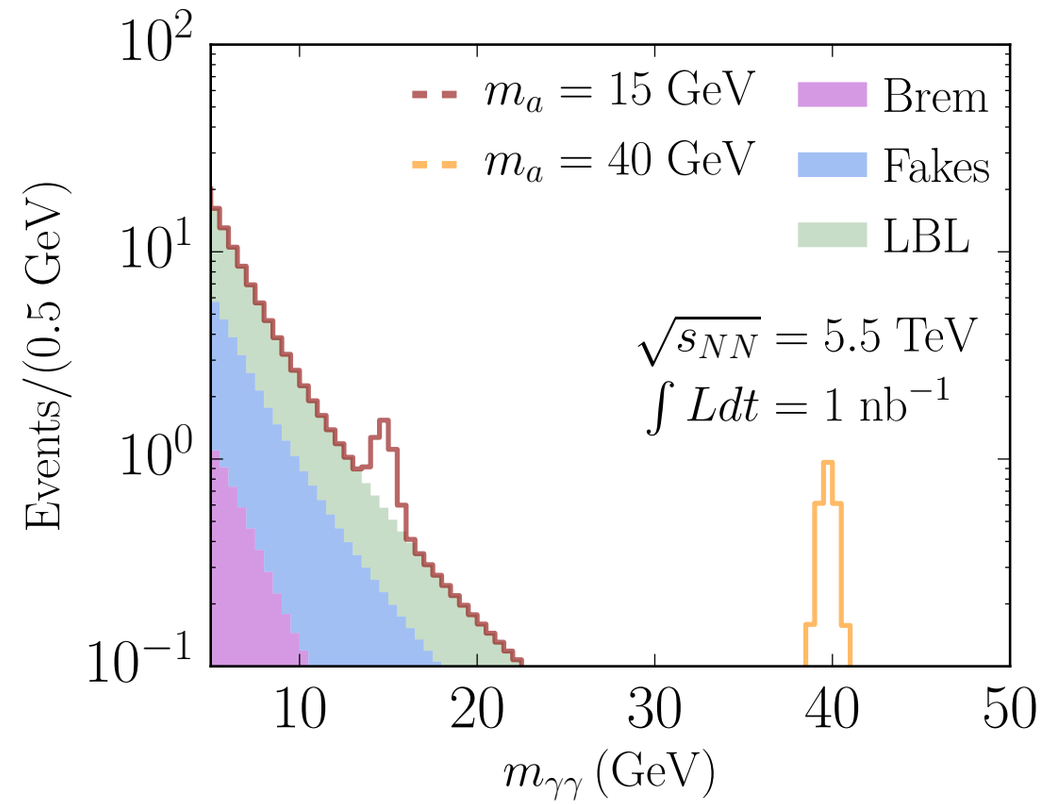
Exclusive Υ production

$$\mathrm{Pb} + \mathrm{Pb} \rightarrow \mathrm{Pb} + \mathrm{Pb} + \Upsilon$$

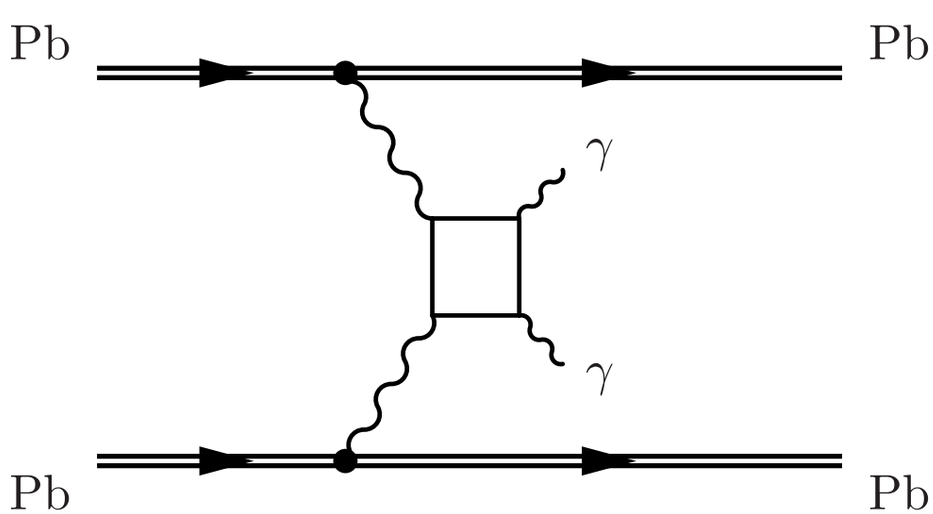
Axion-like particles

Axion-like particles (ALP's): $\mathcal{L} \supset \frac{1}{4\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu}$



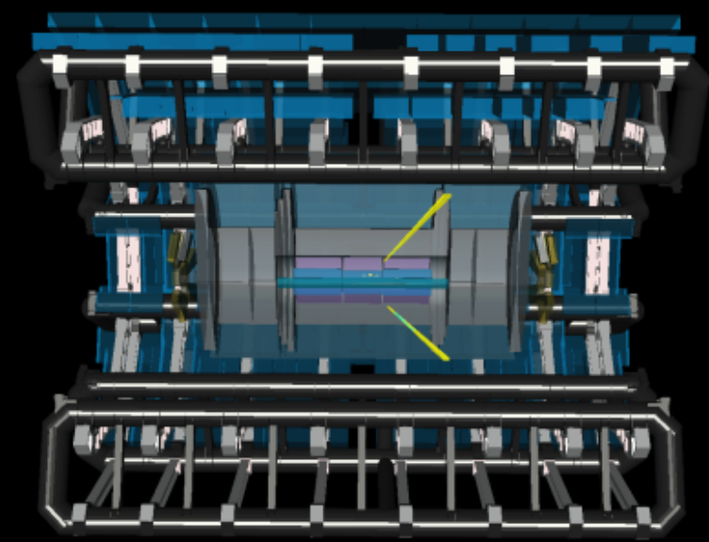


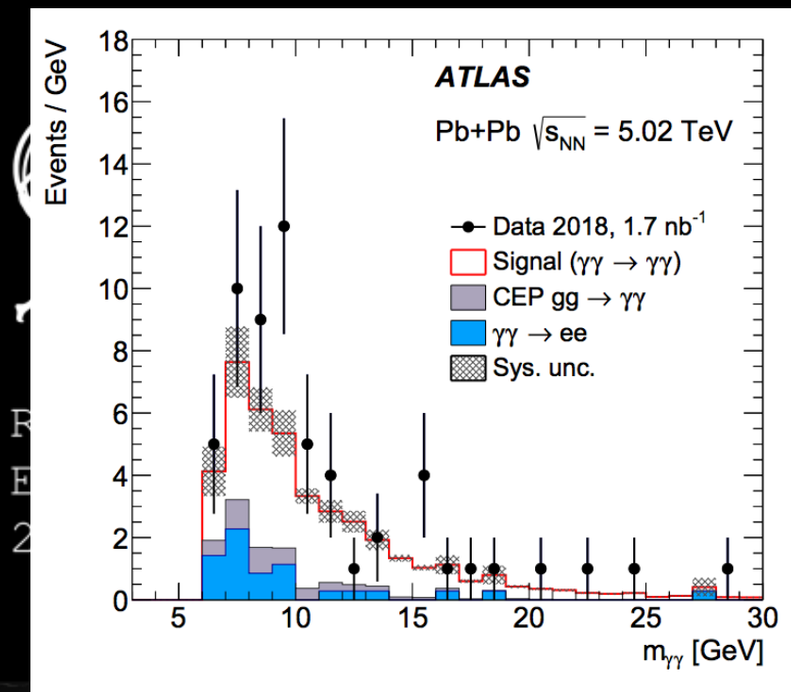
Dominant background: light-by-light scattering!

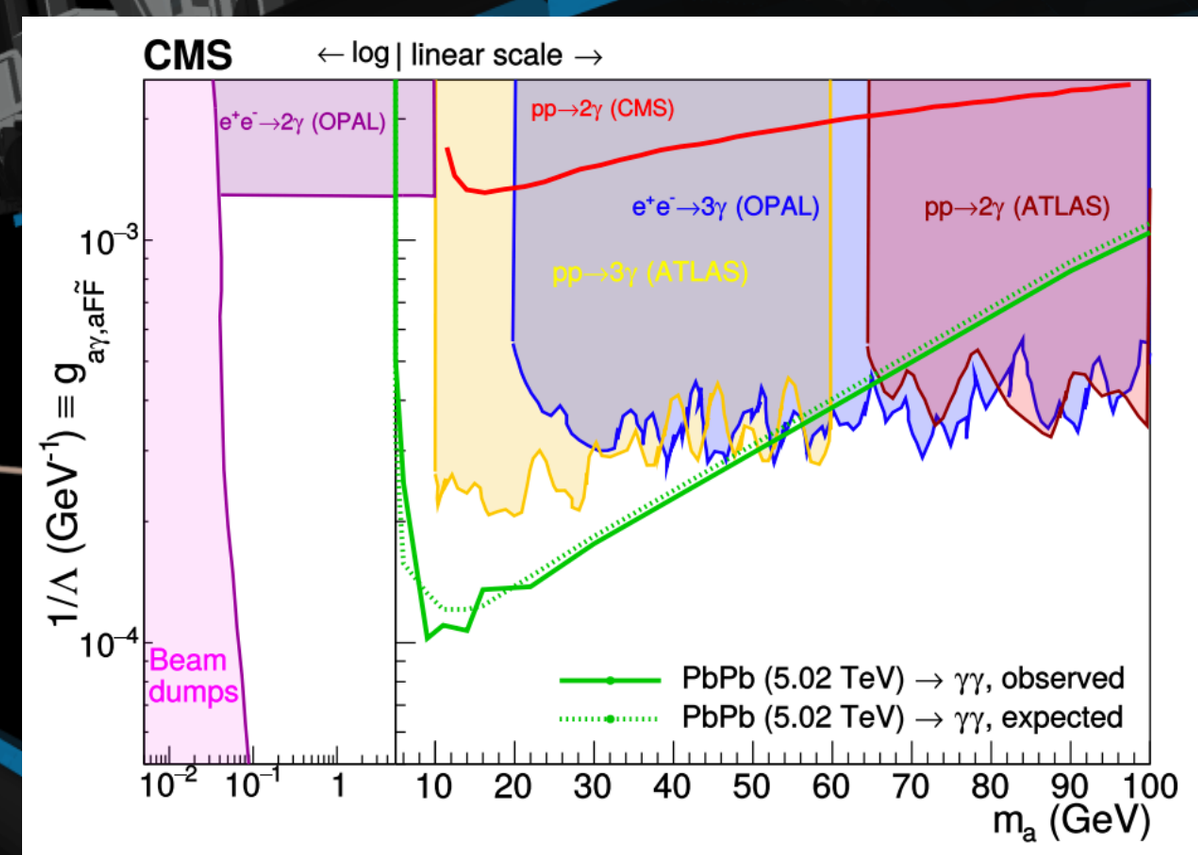


SK, T. Lin, H. K. Lou, T. Melia: 1709.07110
SK, T. Lin, H. K. Lou, T. Melia: 1607.06083

Light-by-light scattering





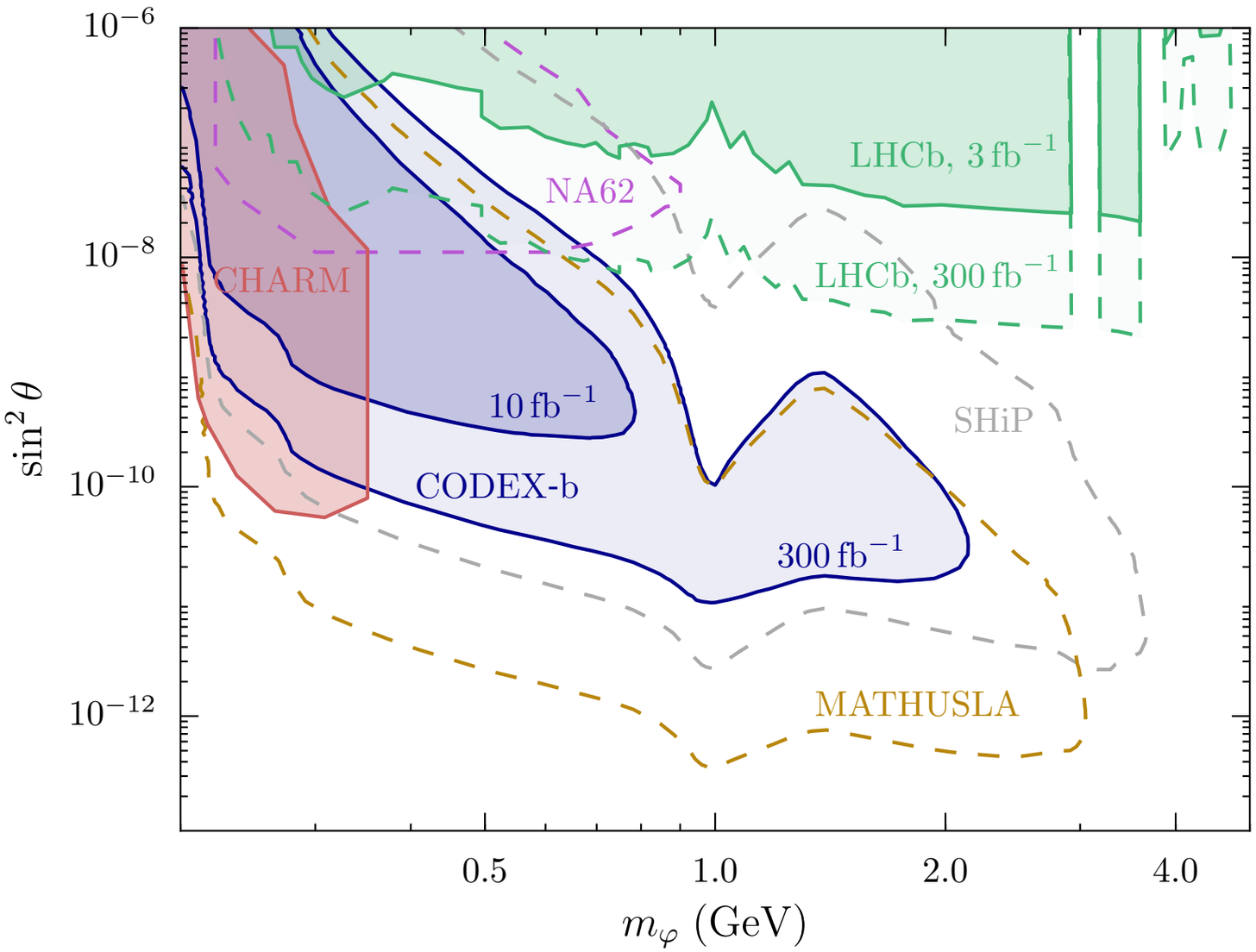


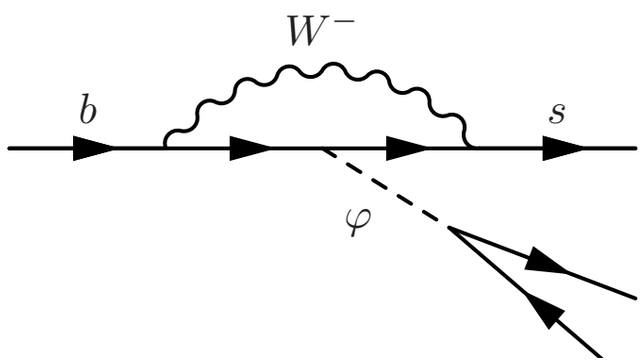
Nature Physics 13 (2017) 852
ATLAS: 1904.03536
CMS: 1810.04602

SK, T. Lin, H. K. Lou, T. Melia: 1709.07110
SK, T. Lin, H. K. Lou, T. Melia: 1607.06083

CODEX-b Reach

Model: $\mathcal{L} \supset \mu\,\varphi H^\dagger H + \frac{\lambda}{2}\,\varphi^2 H^\dagger H$ With $\lambda = 0$



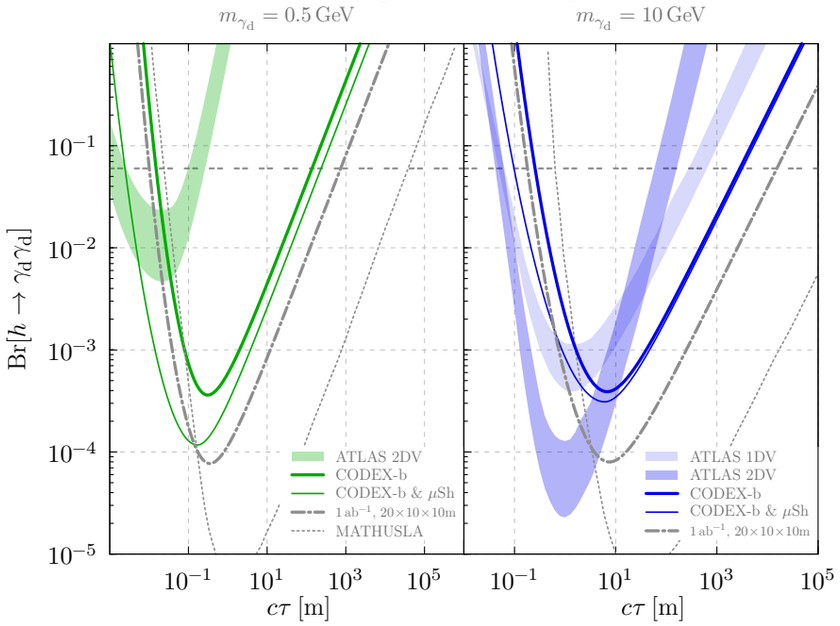


V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243
CODEX-b expression of interest:1911.00481

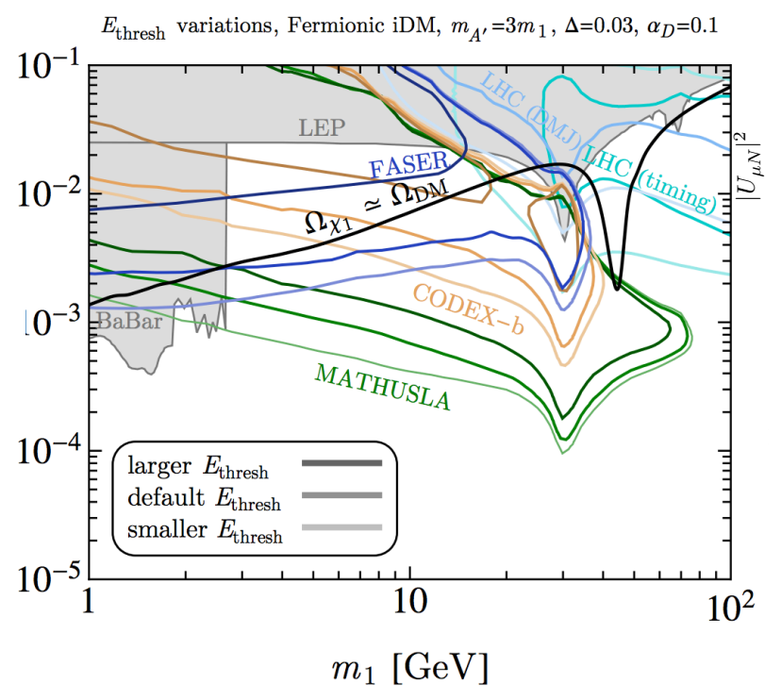
Other models

See CODEX-b "expression of interest": 1911.00481

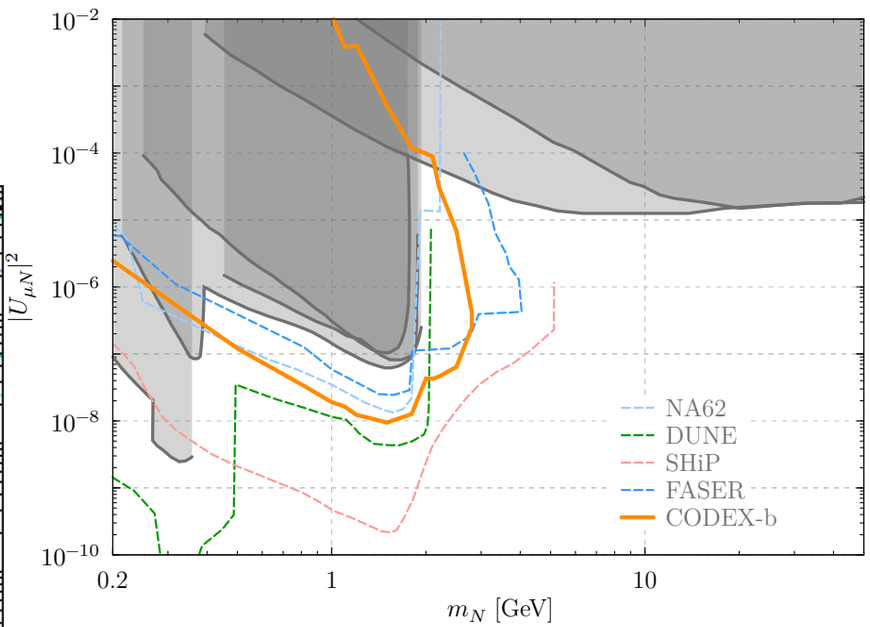
Higgs decays



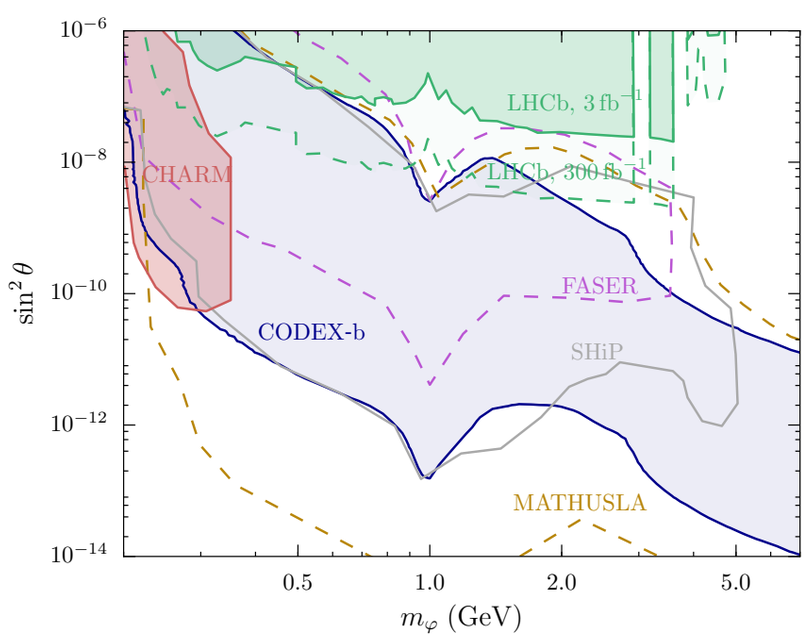
Inelastic dark matter

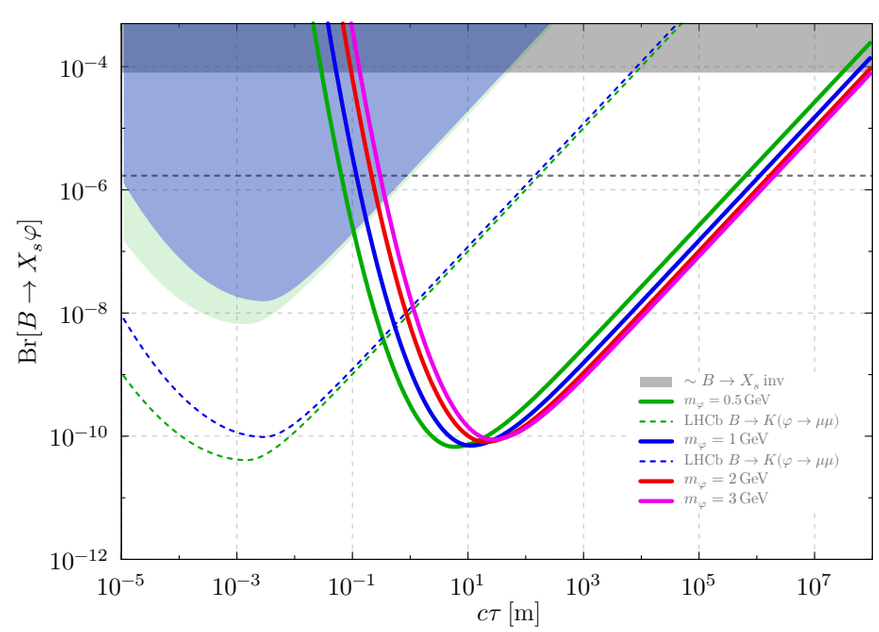


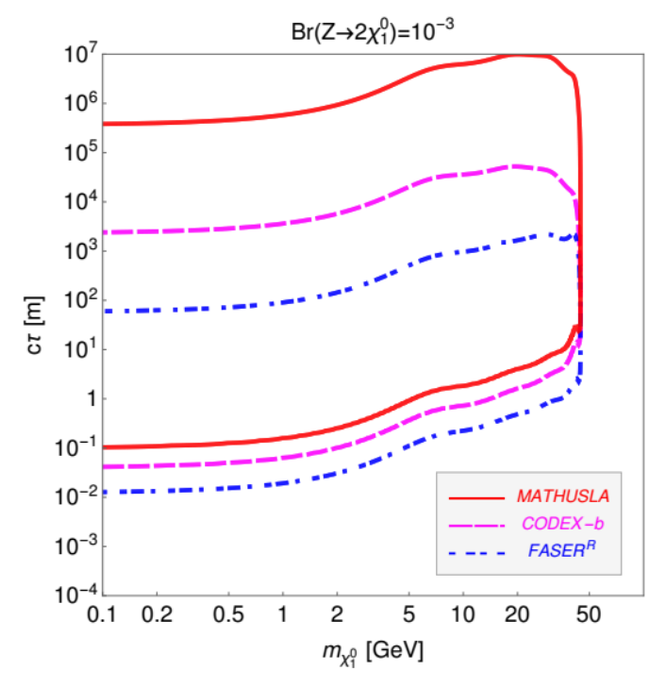
Heavy Neutral Leptons



More B decays



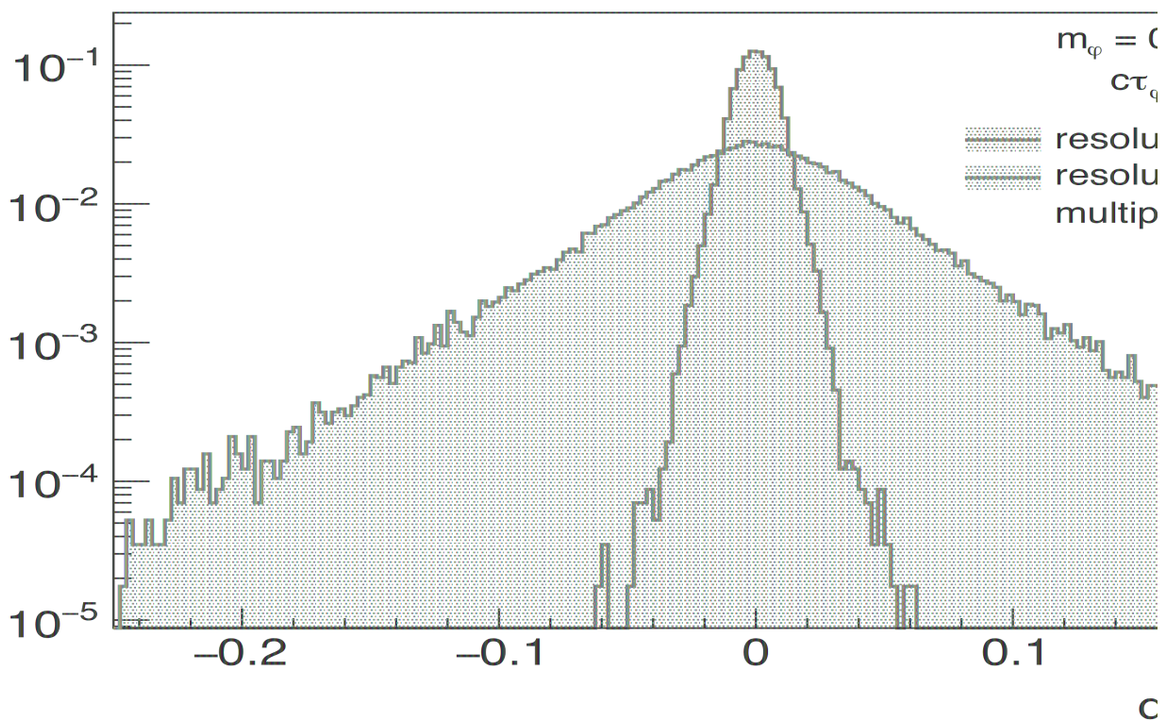




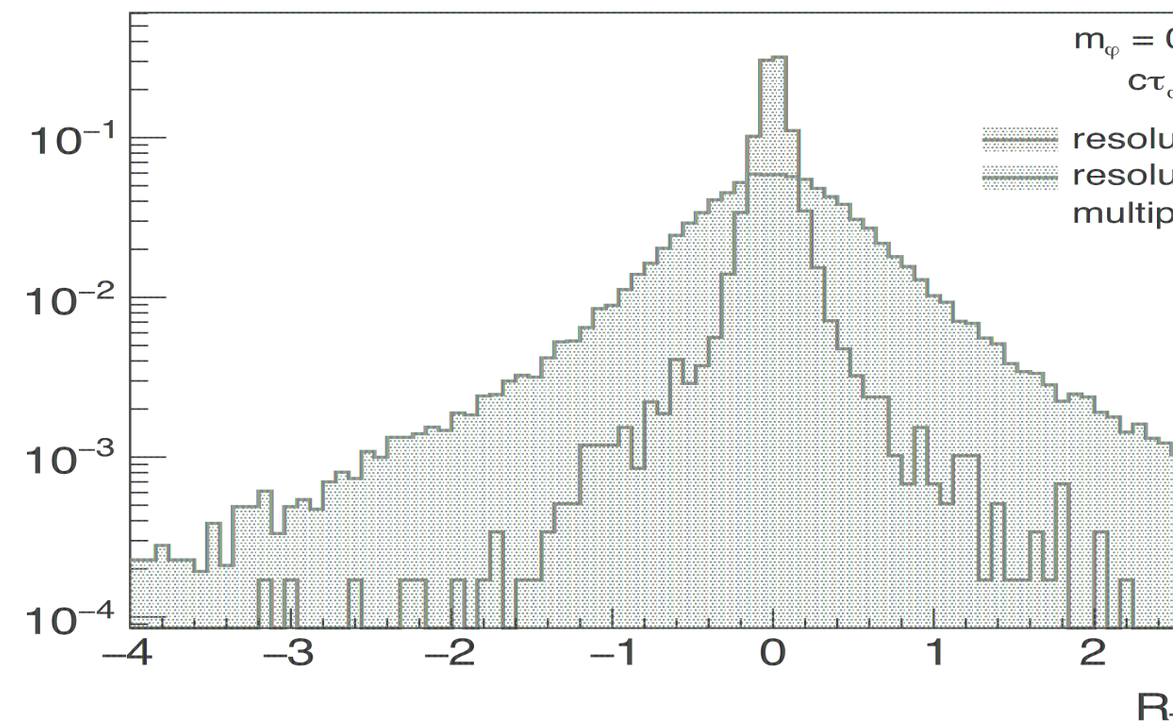
Z decays

Performance

Track impact parameter in transverse plane



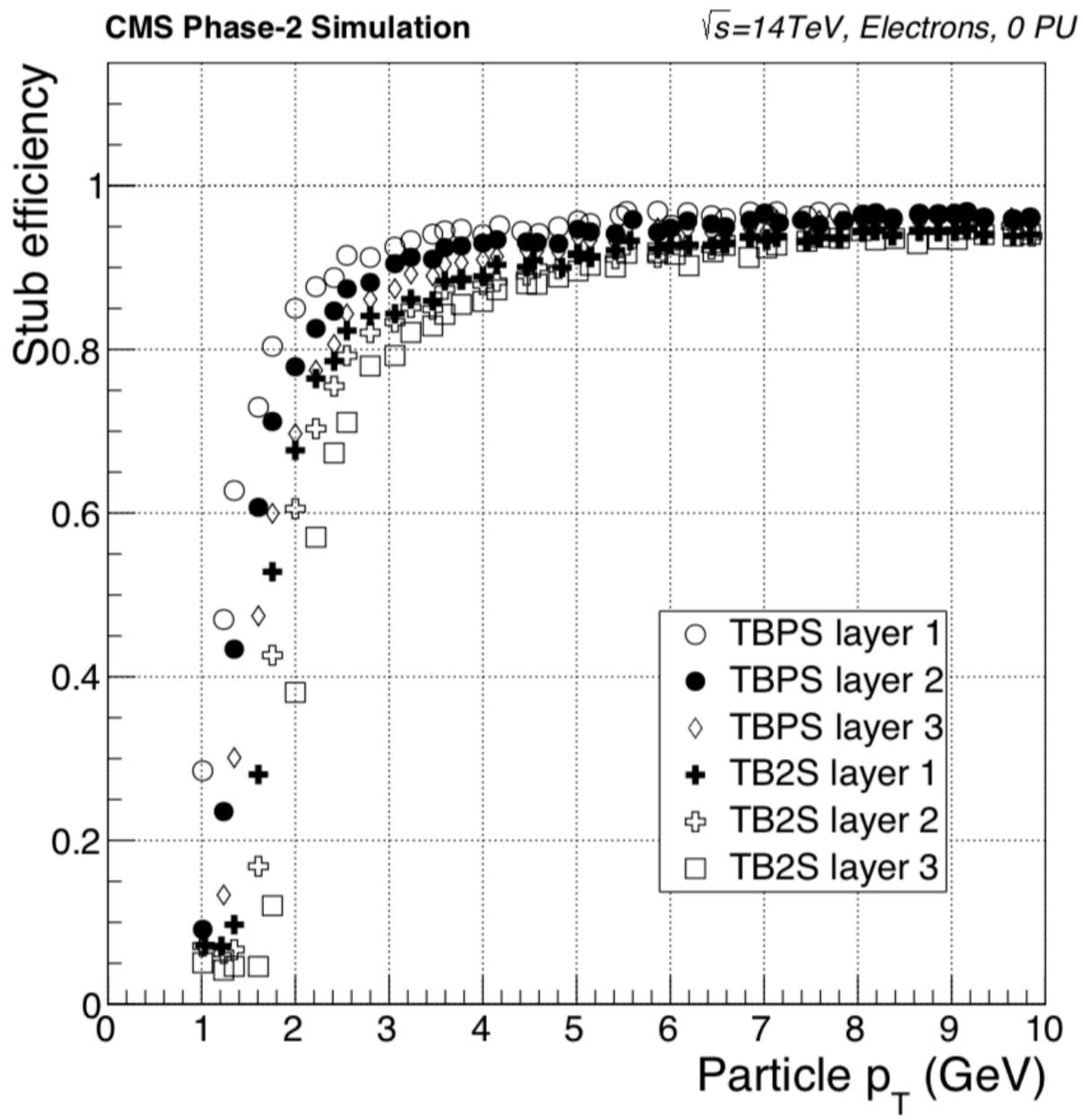
Vertex distance in transverse plane



Fairly good resolution on d_0, resolution on vertex location is poor as expected.

Y. Gershtein, SK: arXiv 1907.00007

Stub reconstruction efficiency



CMS phase II tracker TDR

ATLAS Muon ROI trigger