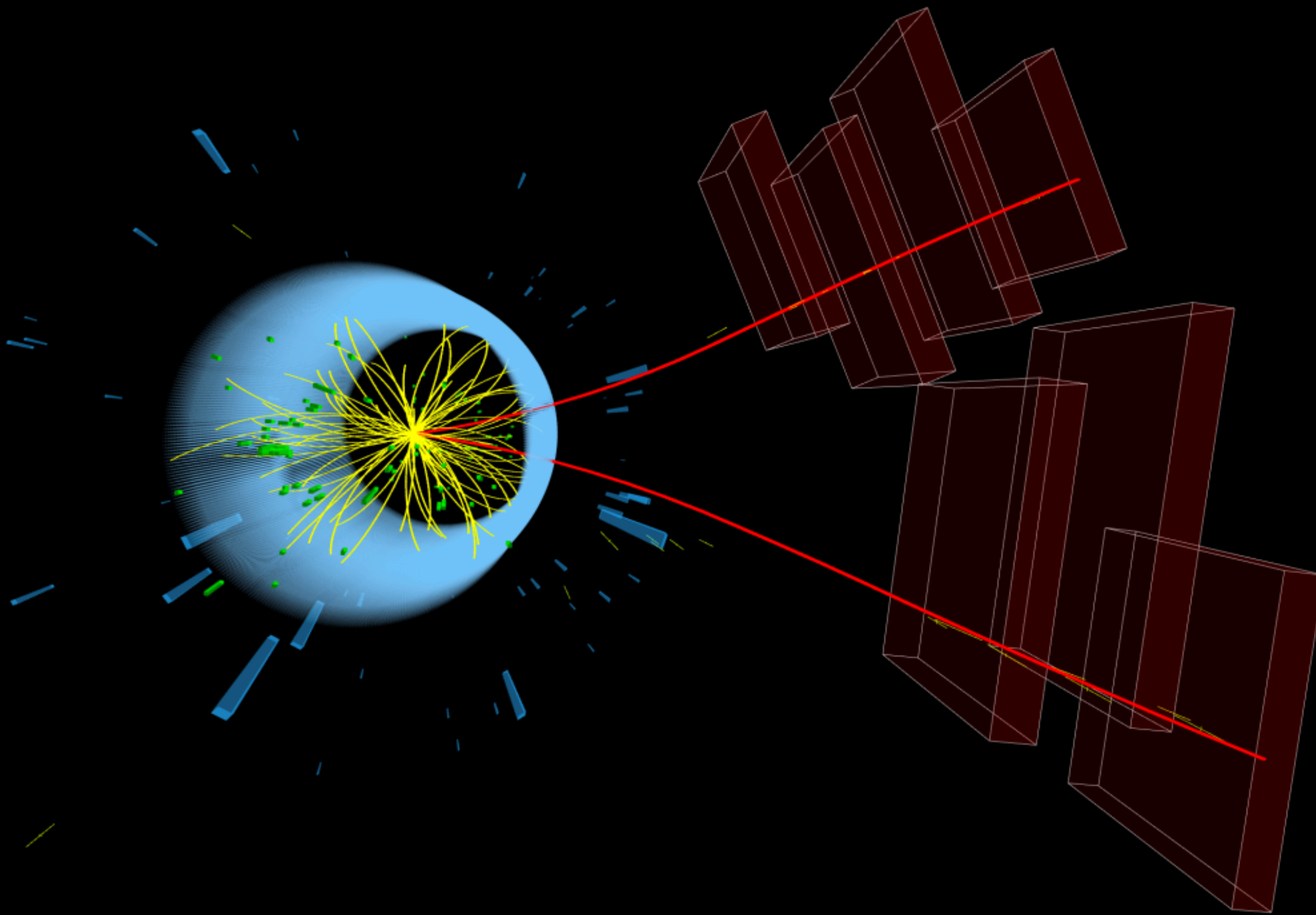
Physics case for displaced vertex triggers during Run 4

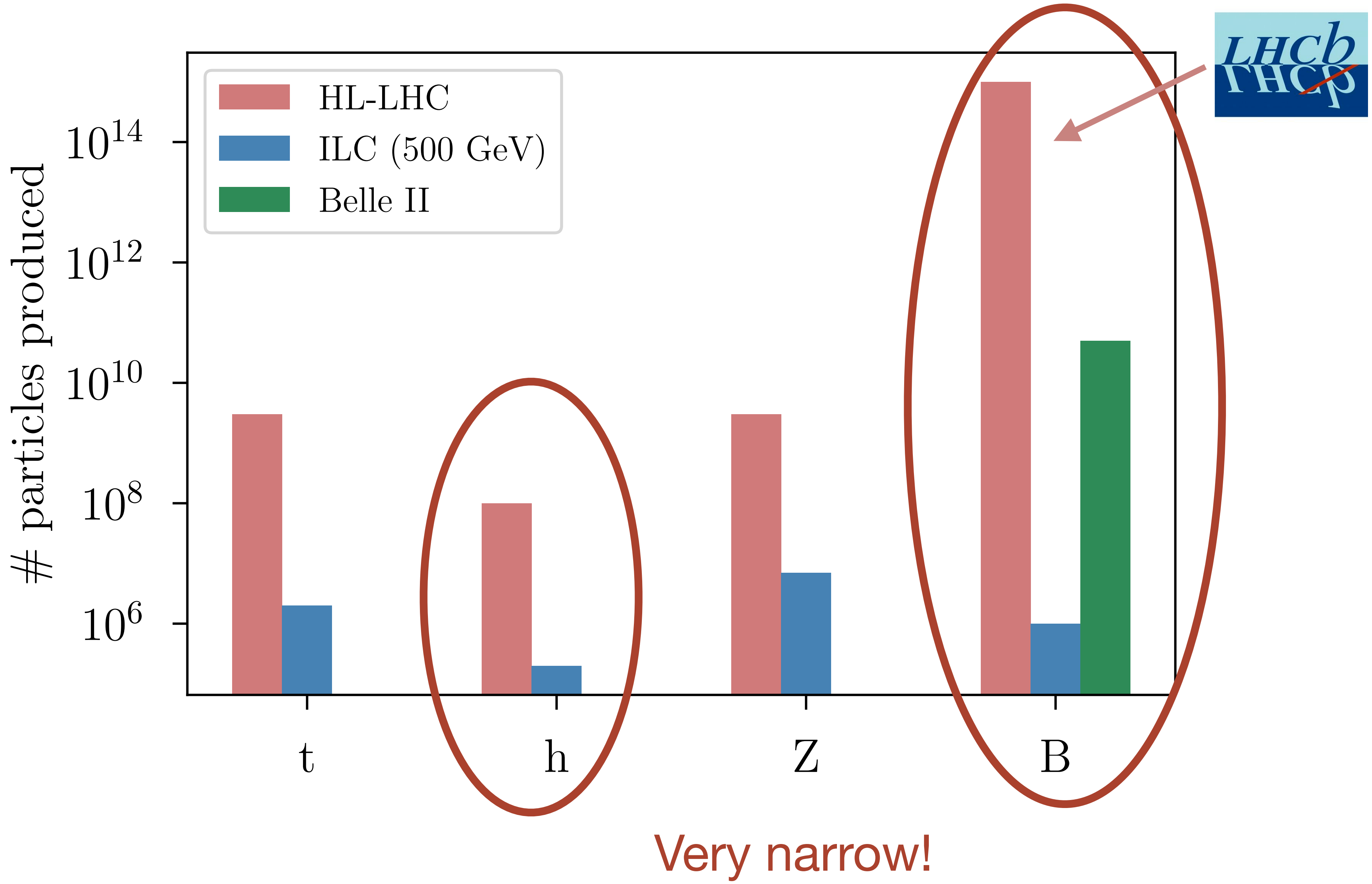


Simon Knapen
CERN

with Yuri Gerhstein, Diego Redigolo

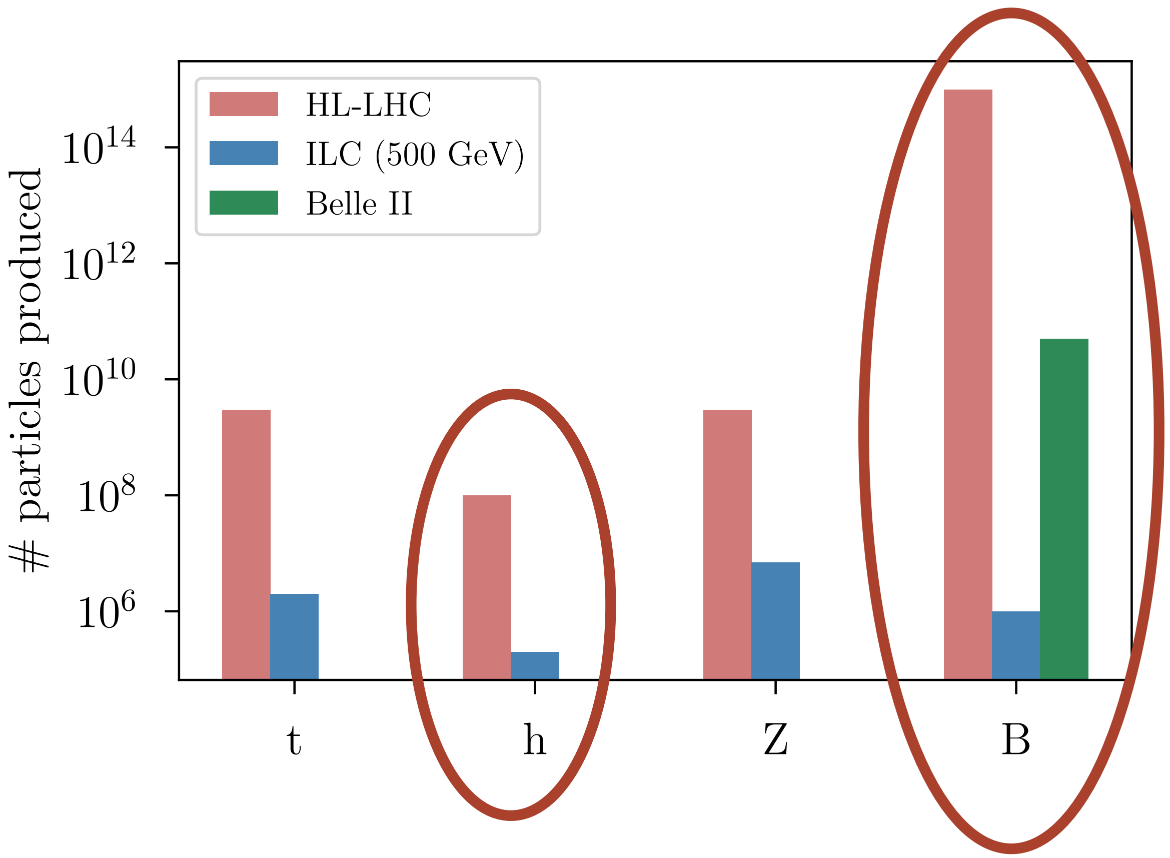
LHC on the intensity frontier

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

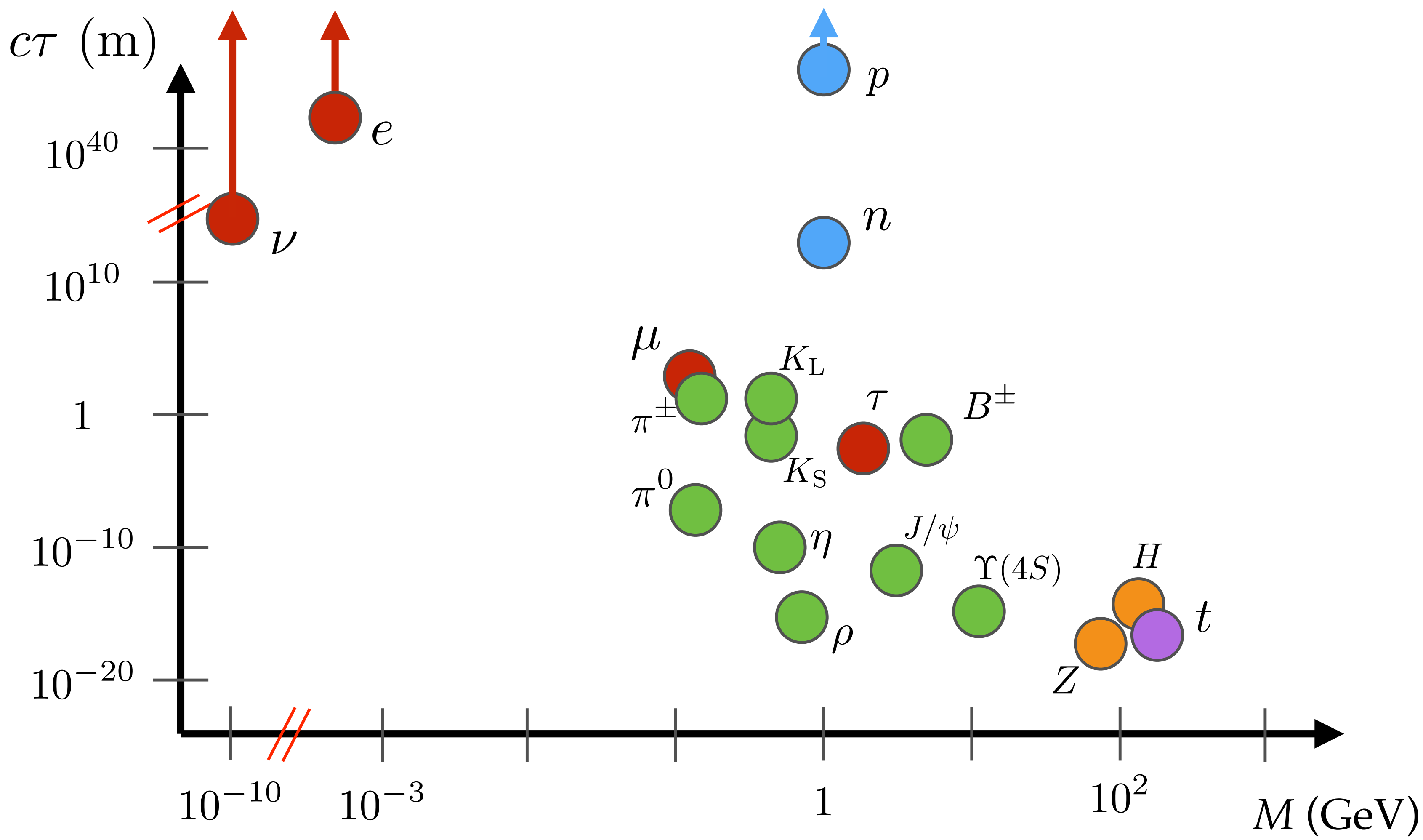
- Low rates
- Relatively low backgrounds (online + offline)

Long Lived particles

Why start with long-lived particles?

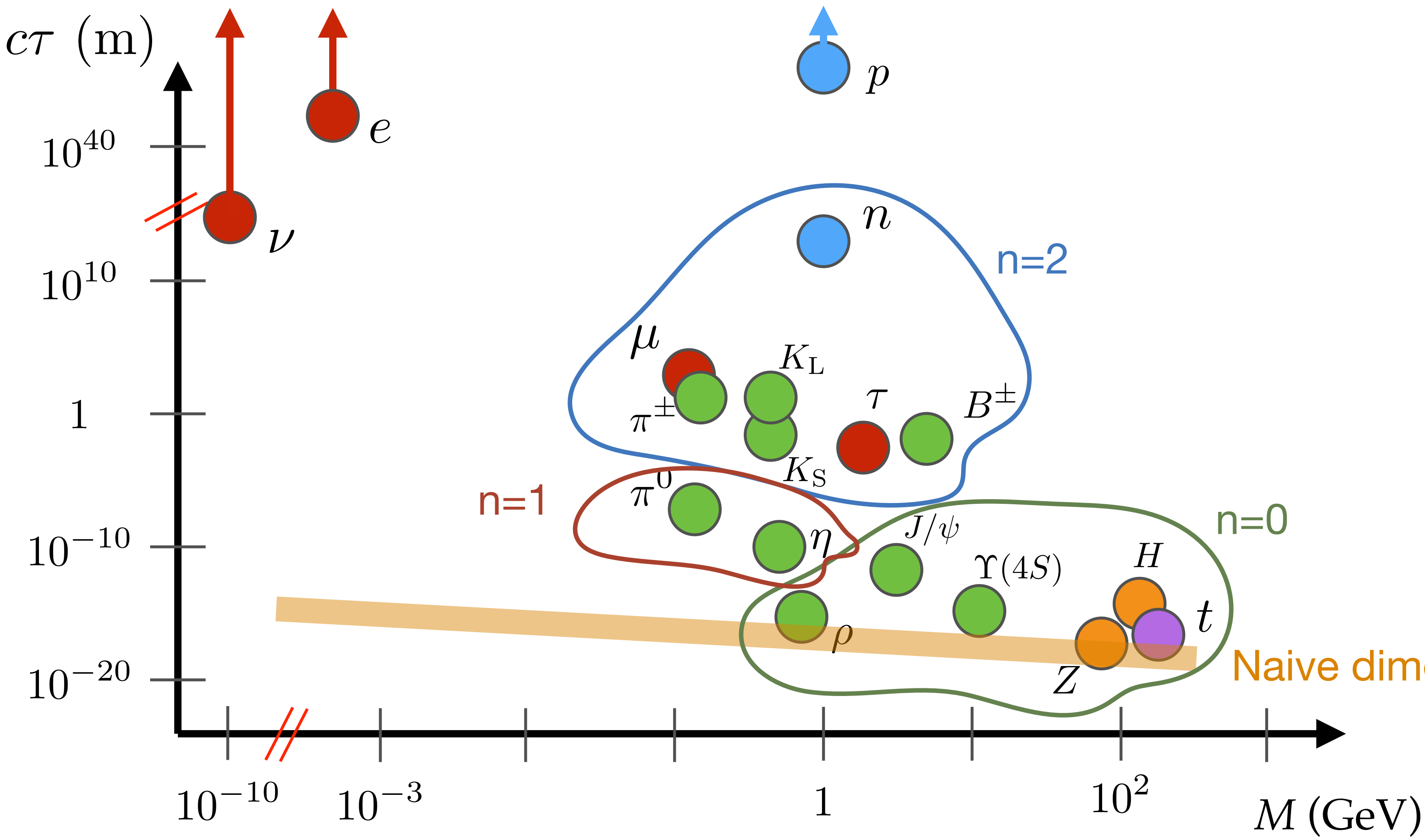
Pragmatic reason: Displaced decay gives new handle to reject backgrounds

Theory reason: Light particles tend to be long-lived



Plot by Brian Shuve

Long Lived particles



Decay width

Positive integer

Particle mass

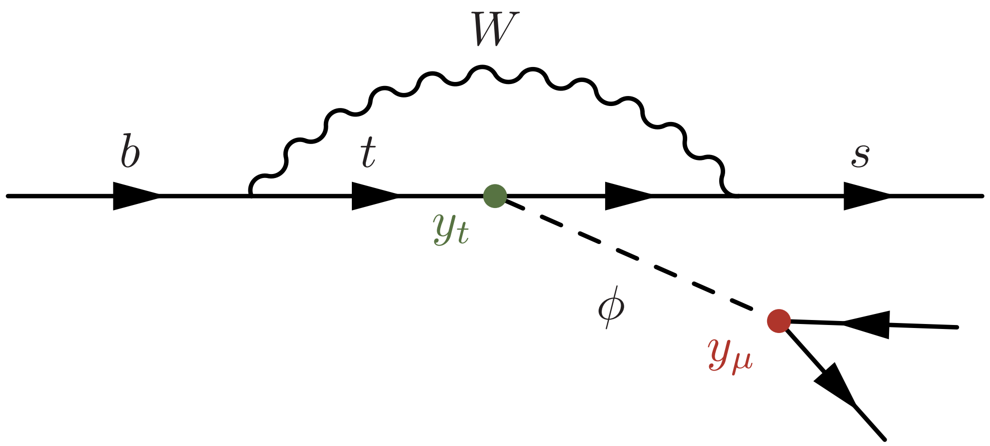
$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

Heavy mass (m_W, Λ_{QCD},…)

A simple example

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

(Most minimal extension of the Standard Model)



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

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

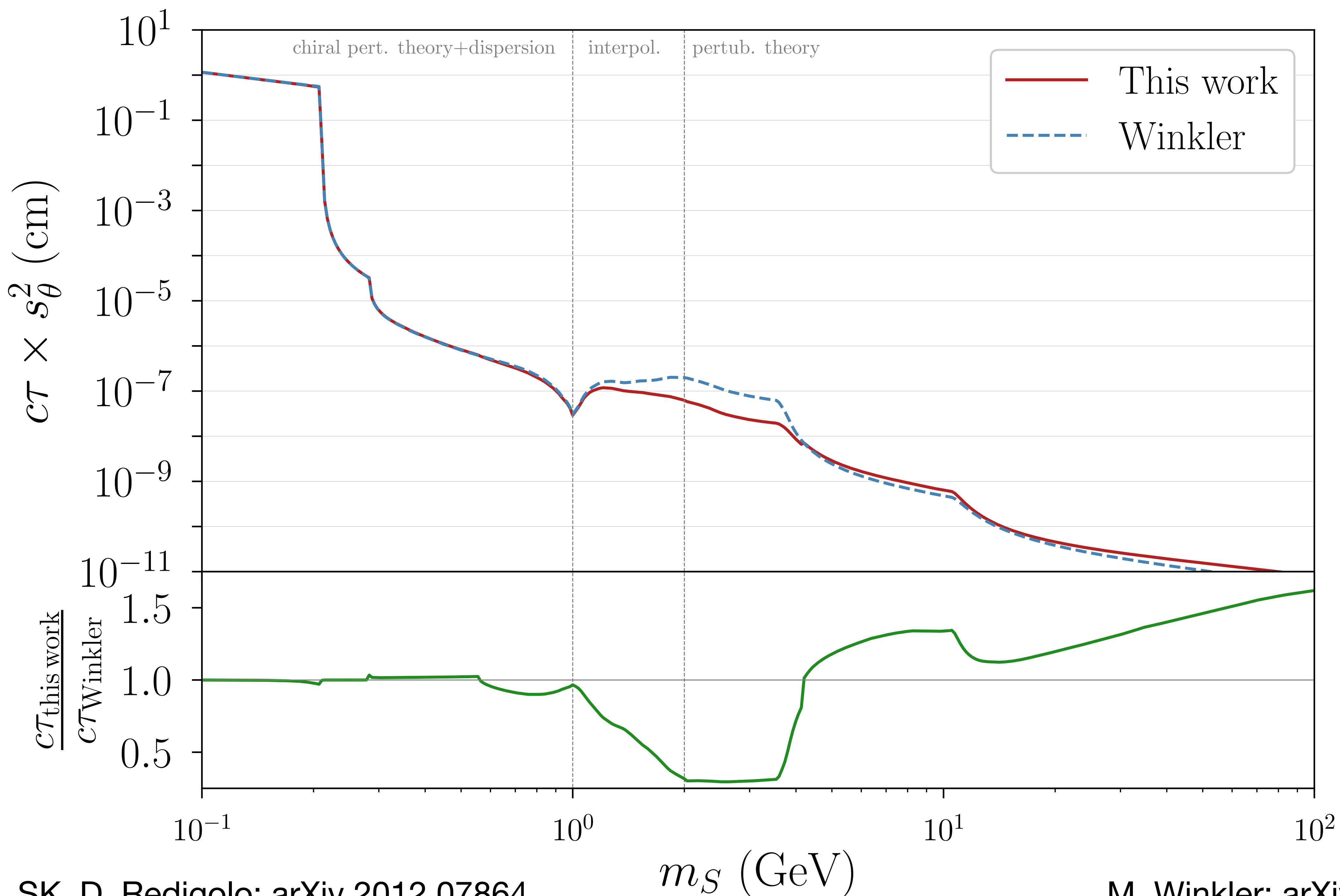
R. S. Willey and H. L. Yu (1982)
R. Chivukula and A. V. Manohar (1988)
B. Grinstein, L. J. Hall, and L. Randal (1988)
B. Batell, M. Pospelov, A. Ritz (0911.4938)
…

A simple example

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

(Most minimal extension of the Standard Model)

<u>Decay</u>:

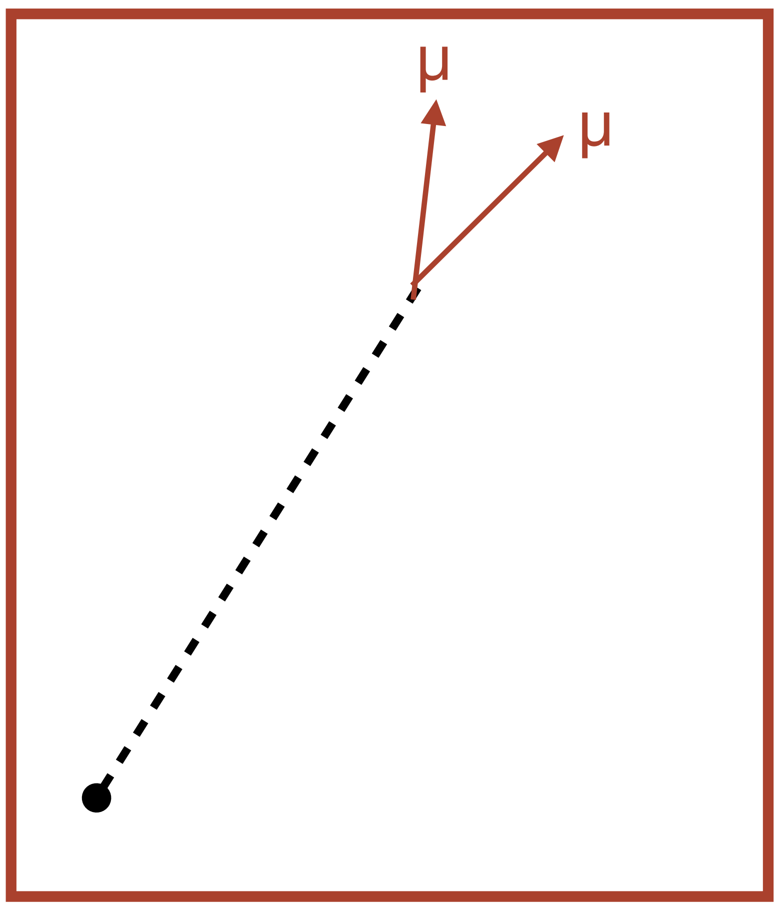


Y. Gerhstein, SK, D. Redigolo: arXiv 2012.07864

M. Winkler: arXiv 1809.01876

Physics case for displaced vertex triggers

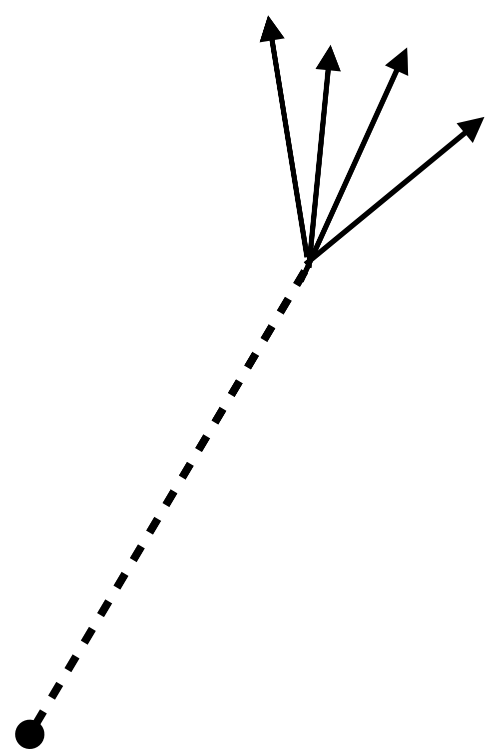
Muonic DV



Exotic B-decays
Dark showers

Y. Gerhstein, SK:
arXiv 1907.00007

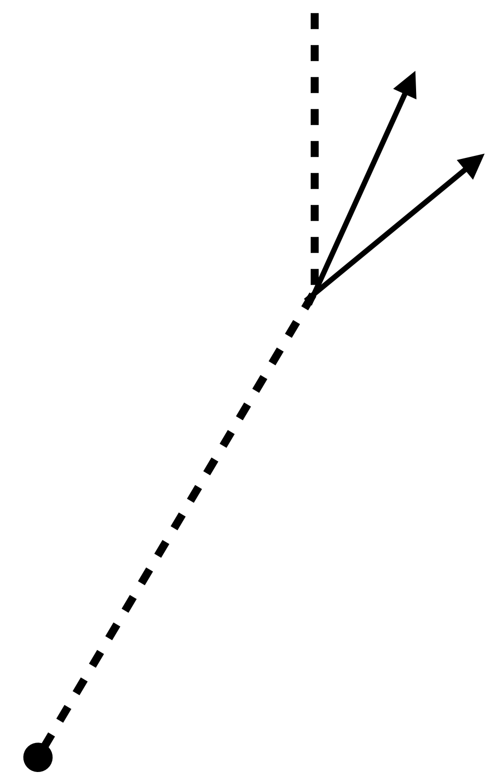
Multi-track DV



Exotic Higgs decays
Axion-like particles

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

DV + MET

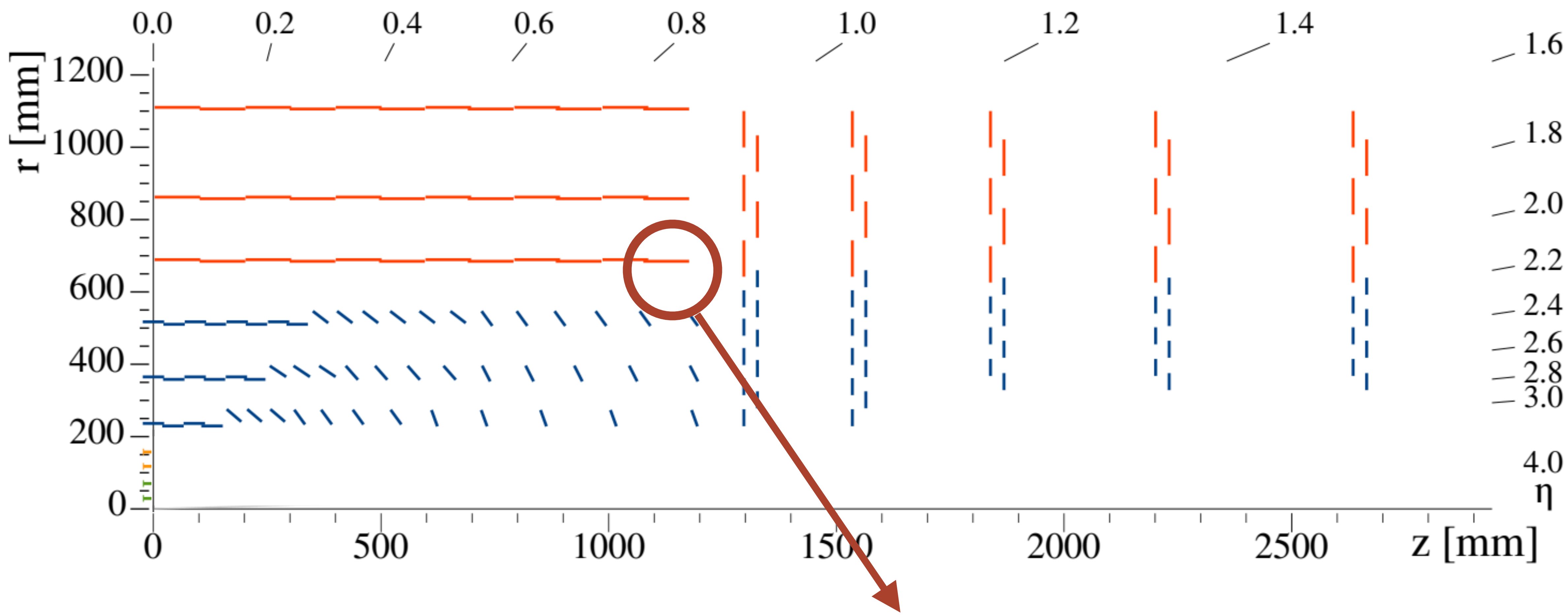


Heavy Neutral Leptons,
Inelastic Dark Matter

Y. Gerhstein, S. Junius, SK, A. Marriotti, D. Redigolo:
in progress

CMS Level 1 track trigger

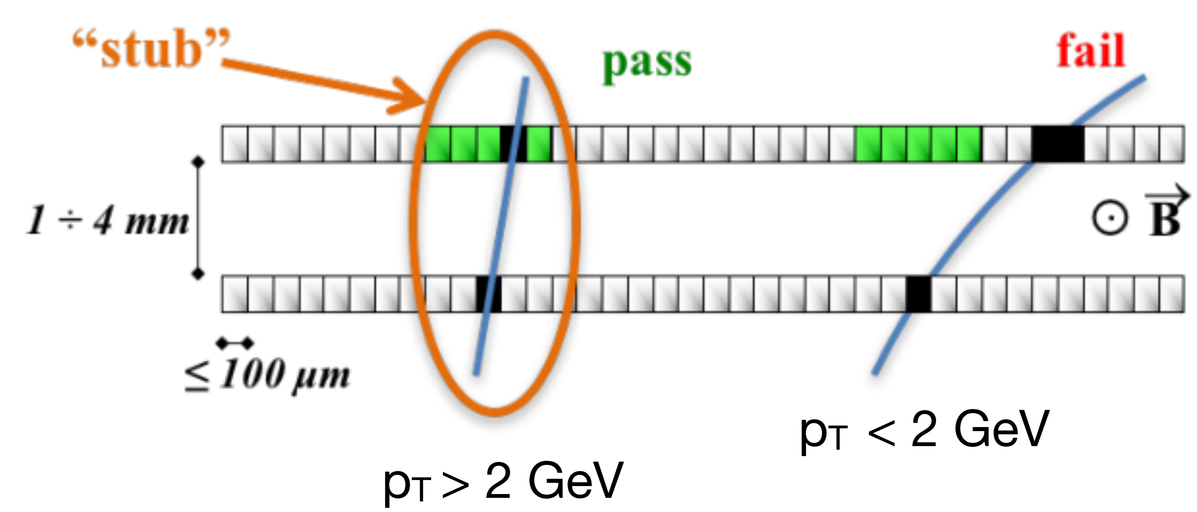
Phase II tracker layout



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

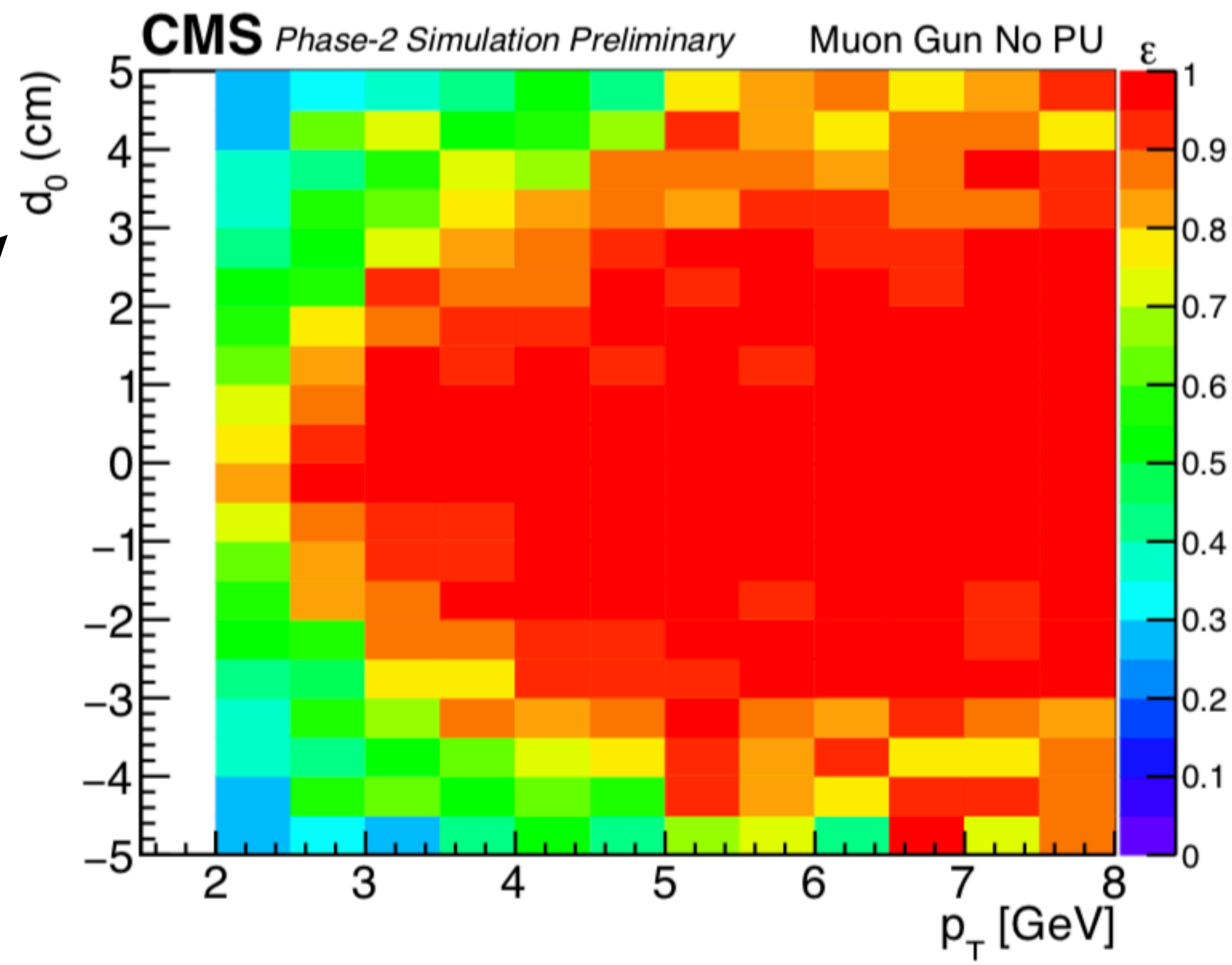
Displaced tracks

Key point: For moderate displacements, stubs are still reconstructed

↓

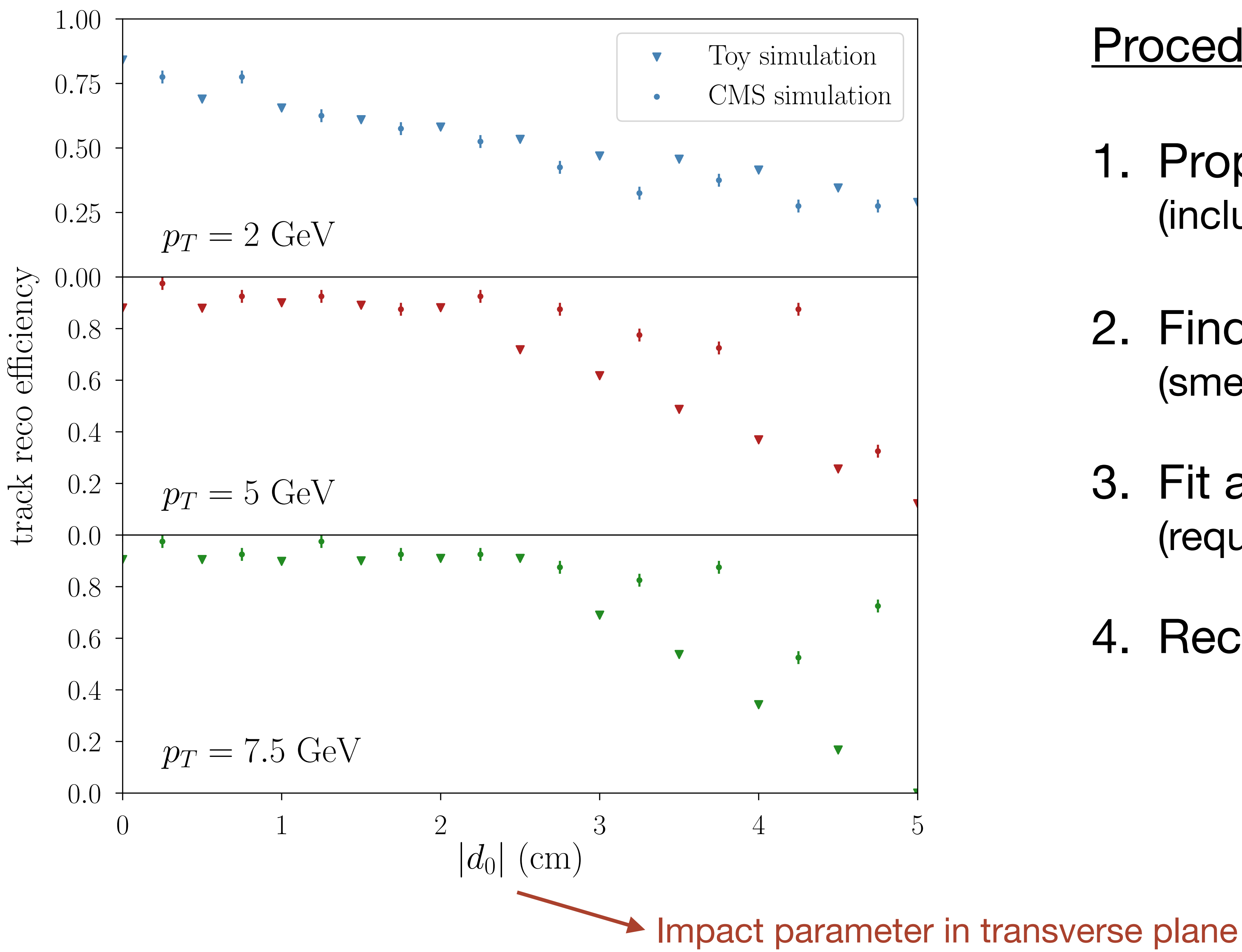
In principle, track trigger could find displaced tracks

Impact parameter in the transverse plane



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

Toy detector simulation



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)

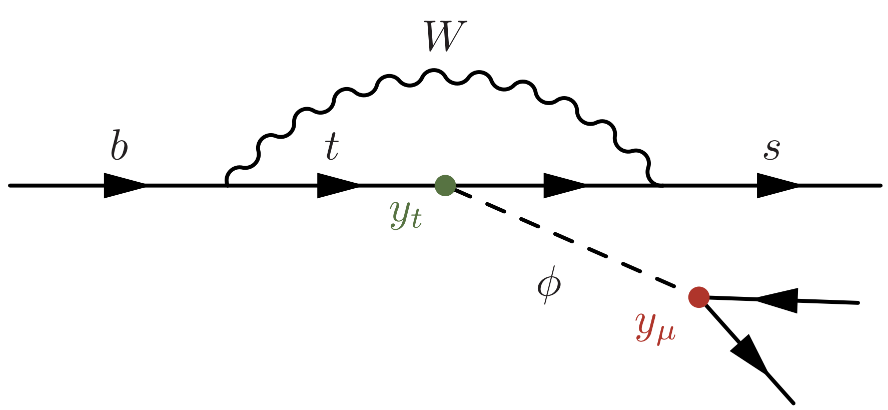
4. Reconstruct a vertex

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

Signal & Background

Signal: displaced dimuon resonance

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



Backgrounds:

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

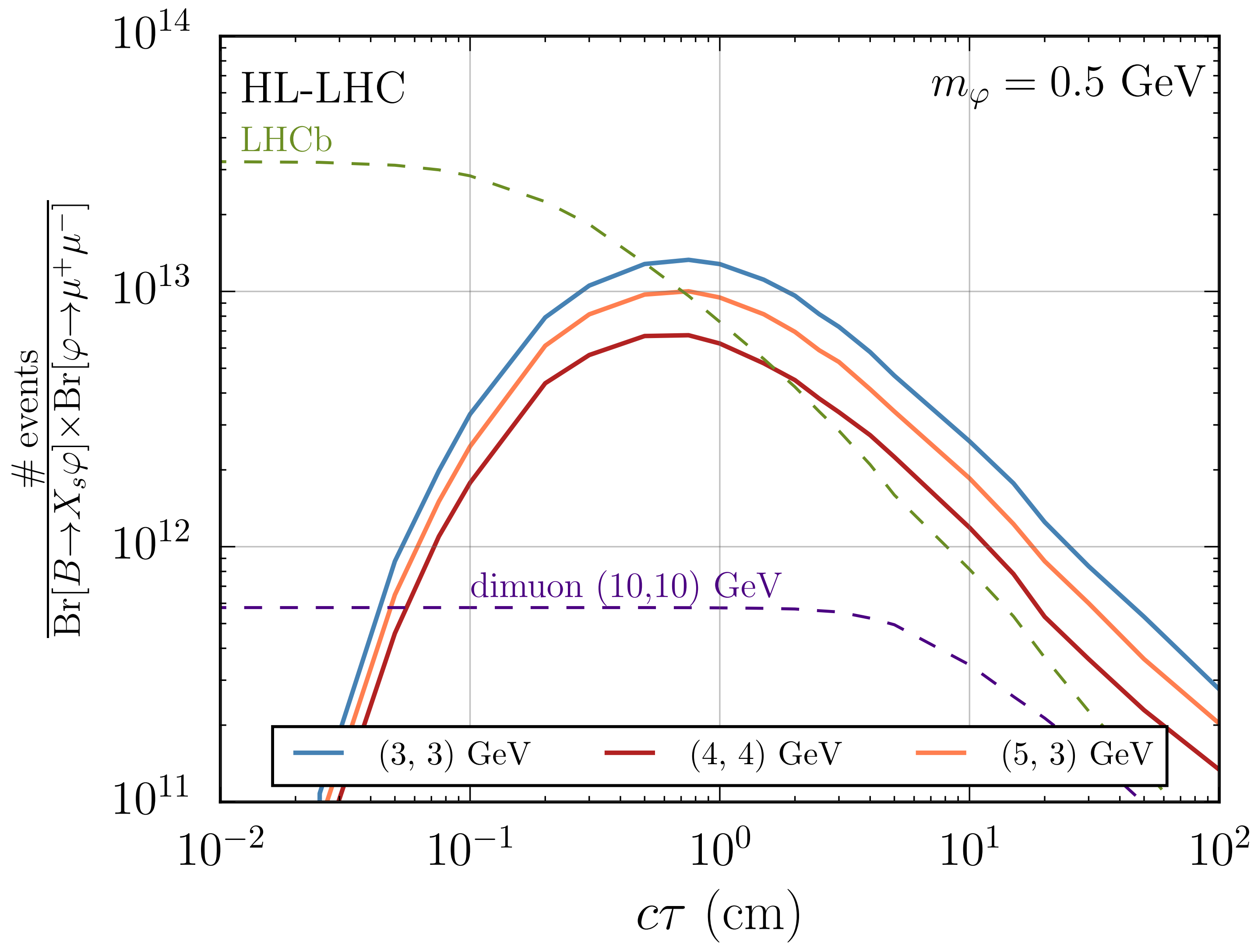
Goal: suppress background factor of 10^{-4} with minimal cuts on signal

Y. Gershtein, SK: arXiv 1907.00007

(Plots in back-up slides)

Trigger yield

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



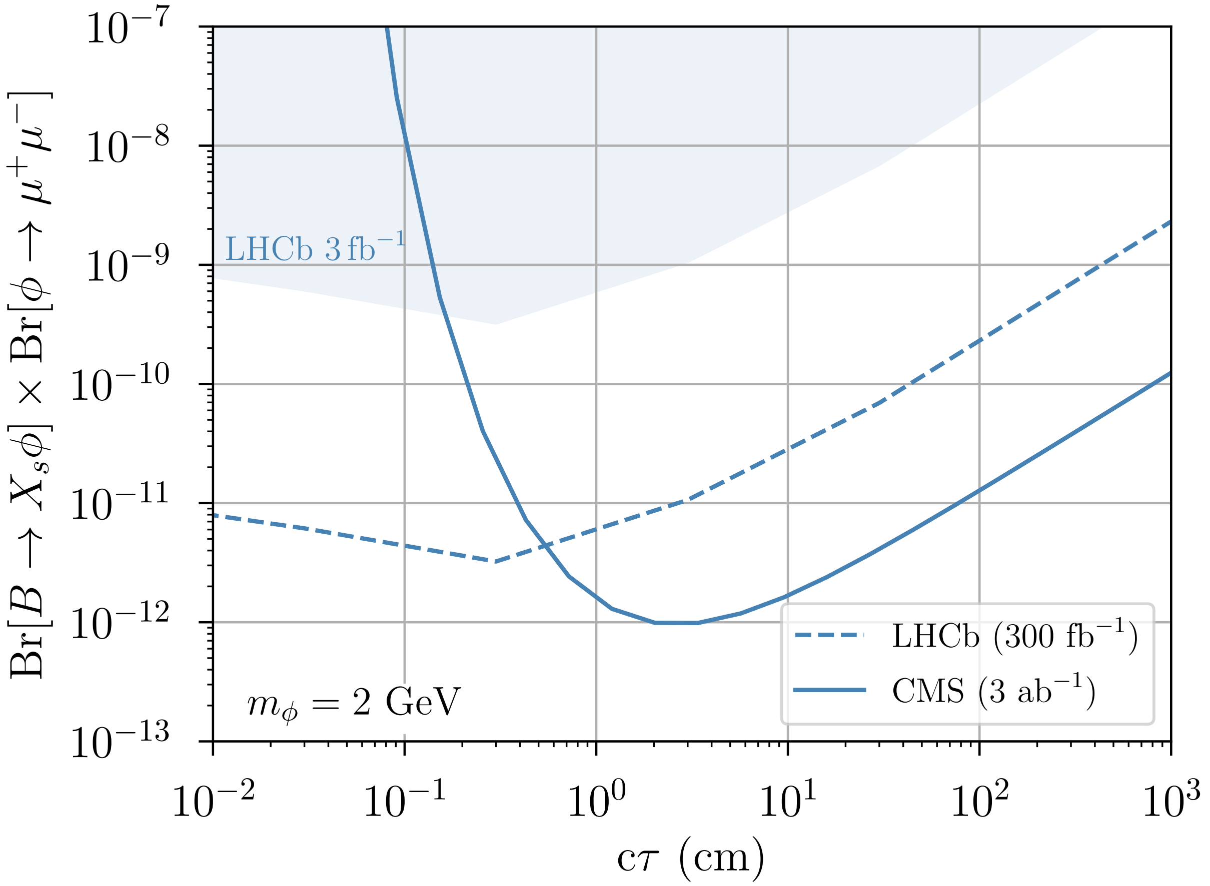
Competitive with LHCb, much better than a (generous) normal dimuon trigger

Y. Gershtein, SK: arXiv 1907.00007

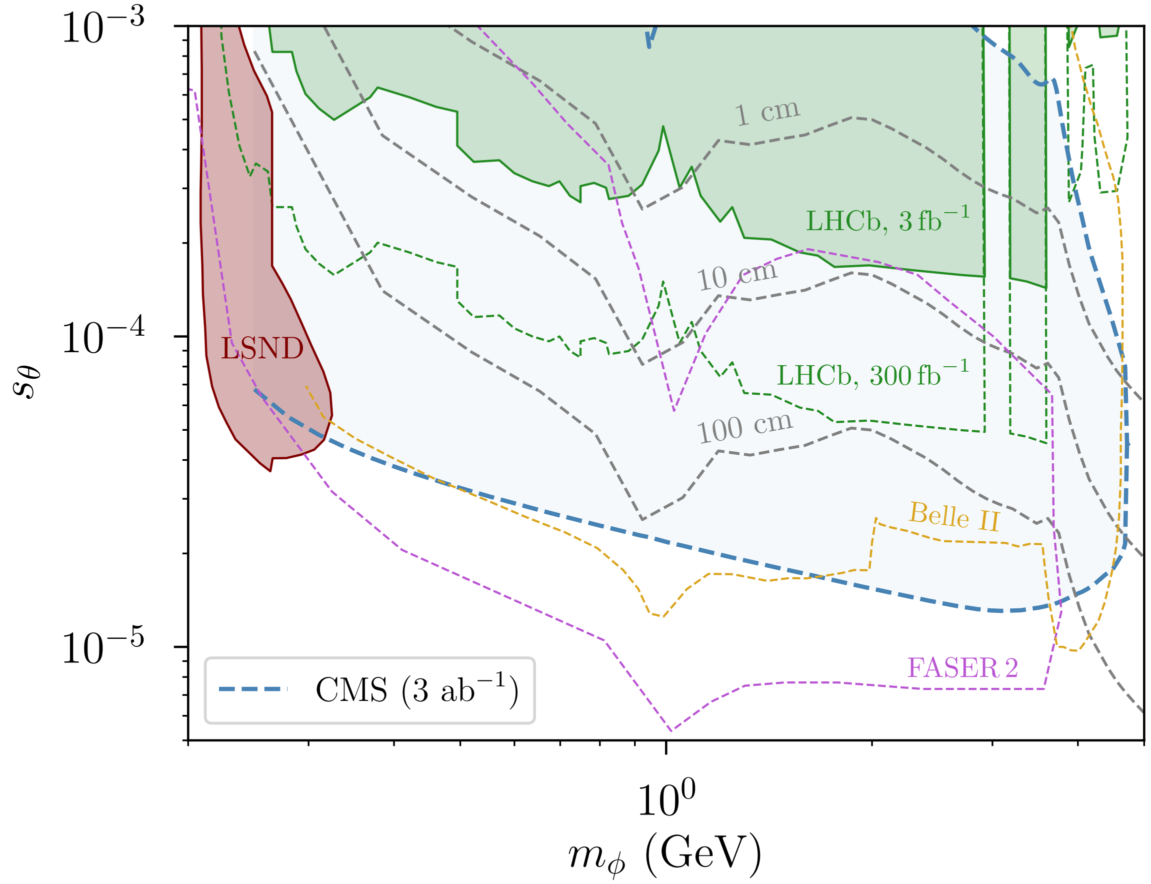
Projected sensitivity

<u>Reach:</u>

Model independent



Scalar mixing with Higgs



CMS reach is a bit optimistic, since detector backgrounds are not modeled

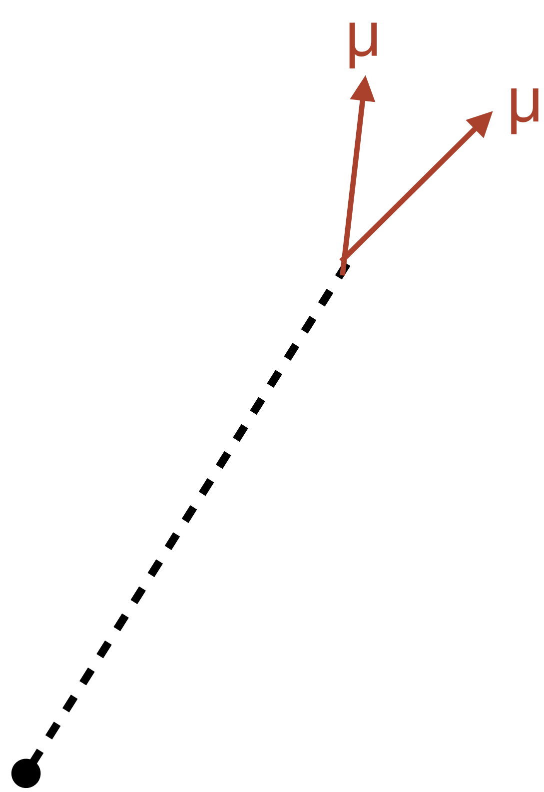
LHCb reach (optimistically) rescaled from current limits

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

(Plots in back-up slides)

Physics case for displaced vertex triggers

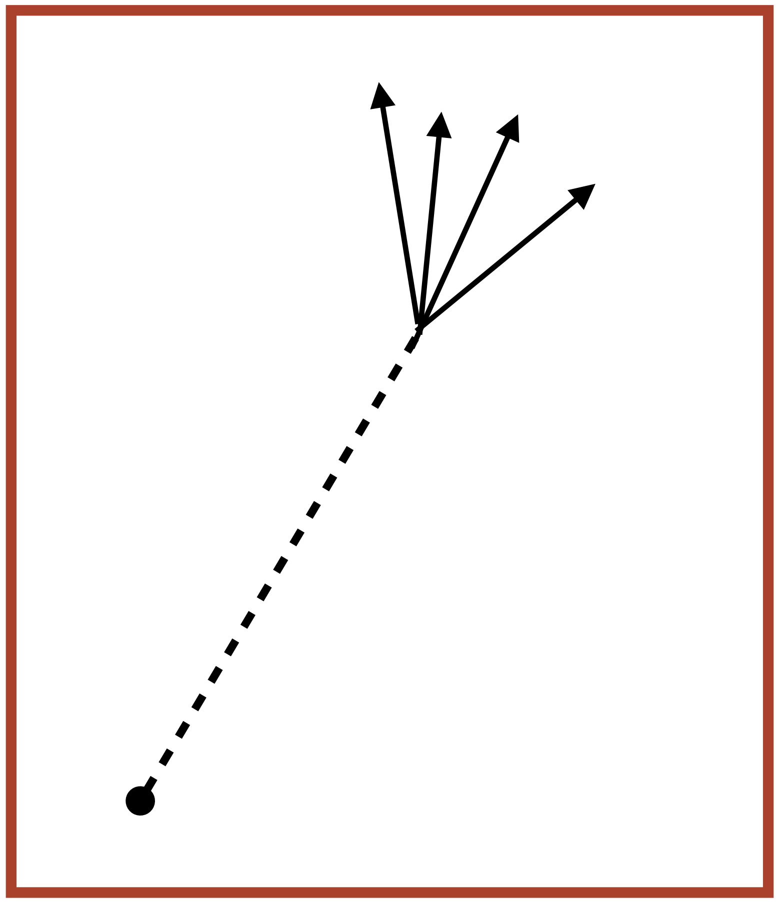
Muonic DV



Exotic B-decays
Dark showers

Y. Gerhstein, SK:
arXiv 1907.00007

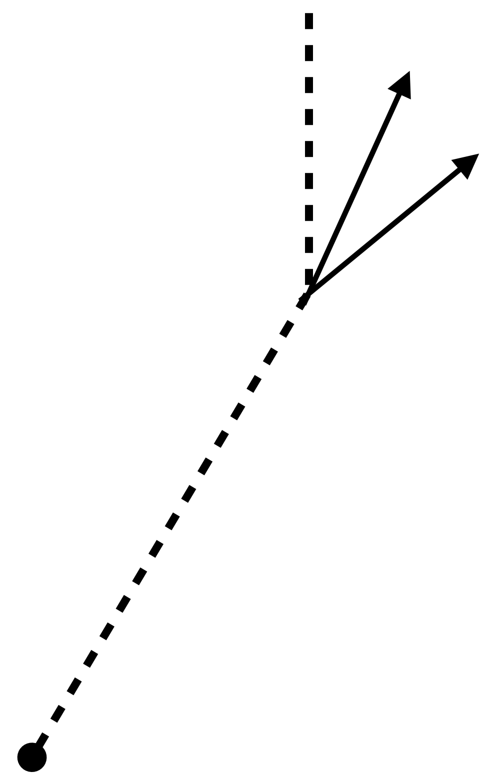
Multi-track DV



Exotic Higgs decays
Axion-like particles

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

DV + MET

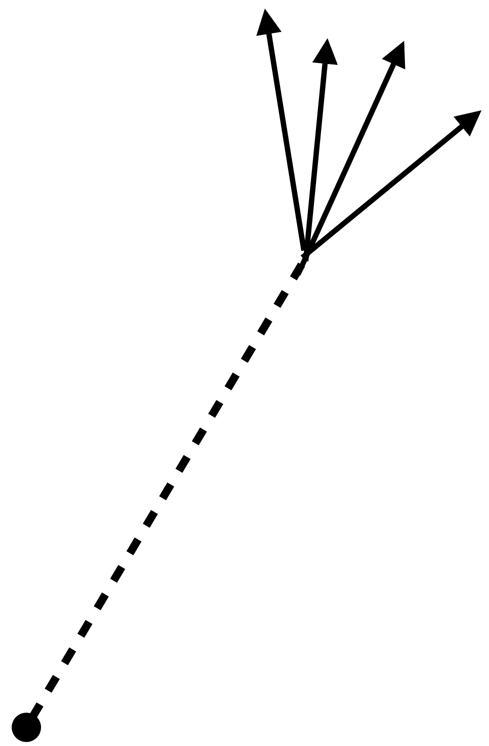


Heavy Neutral Leptons,
Inelastic Dark Matter

Y. Gerhstein, S. Junius, SK, A. Marriotti, D. Redigolo:
in progress

Other applications

Multi-track DV



Axion-like particles
Exotic Higgs decays

Selection

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

Backgrounds

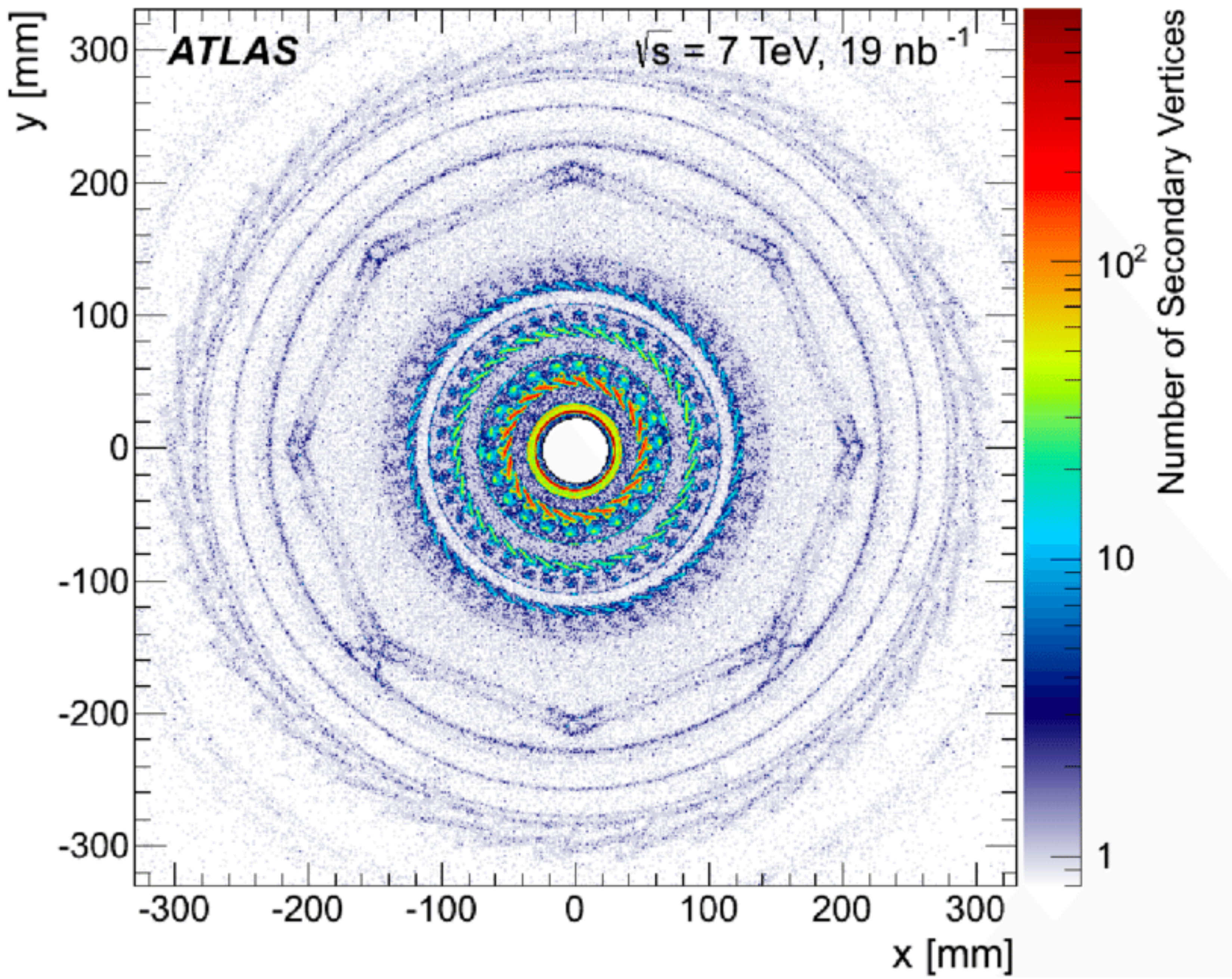
- Fake vertices → ≥ 4 tracks
- B-mesons → Vertex distance
- Material interactions → ??

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

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

Material interactions

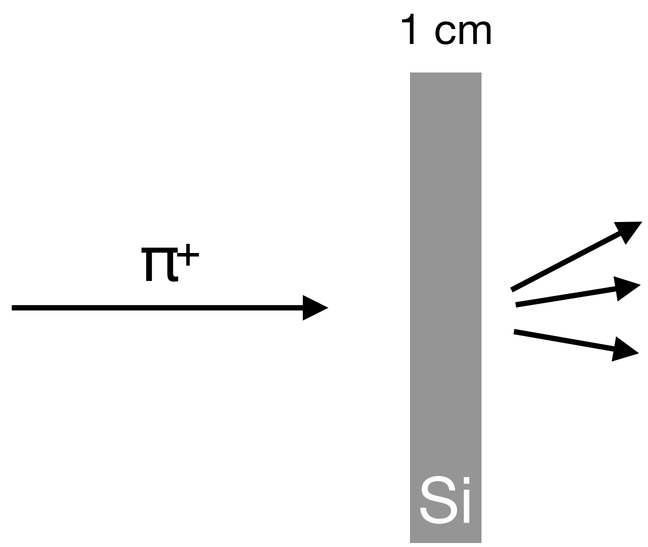
Standard Model particles create secondaries in detector material

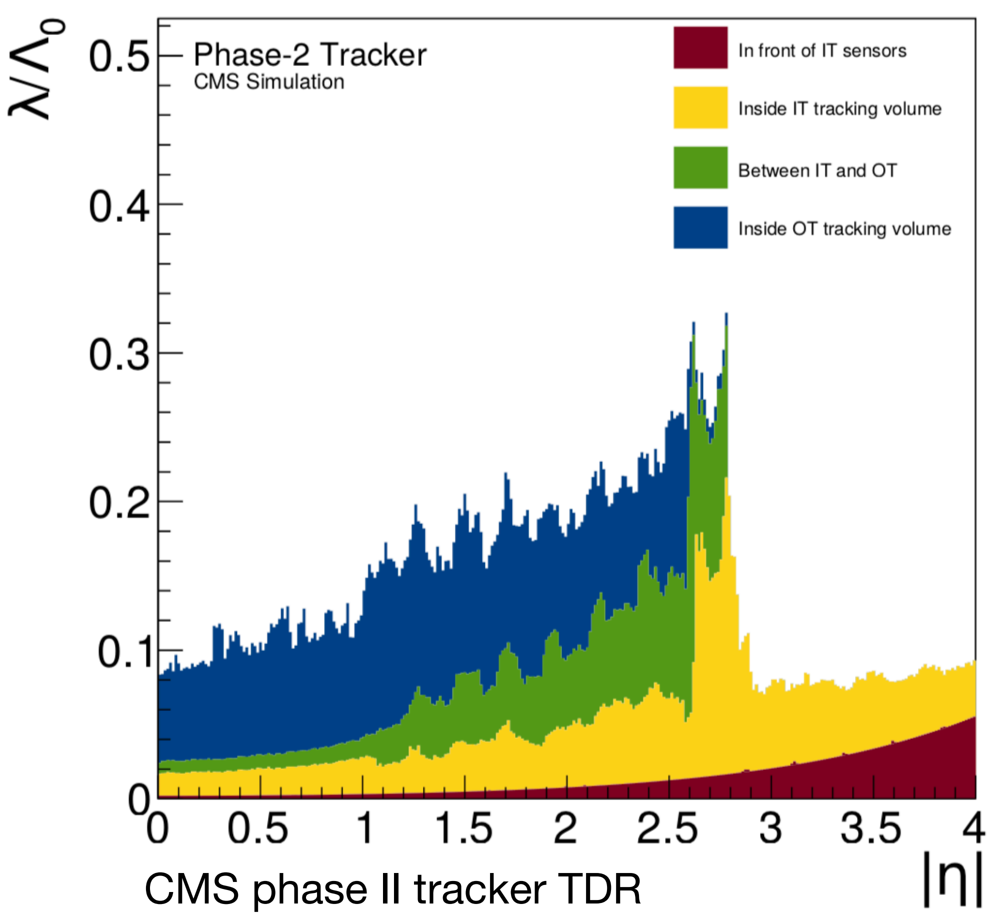


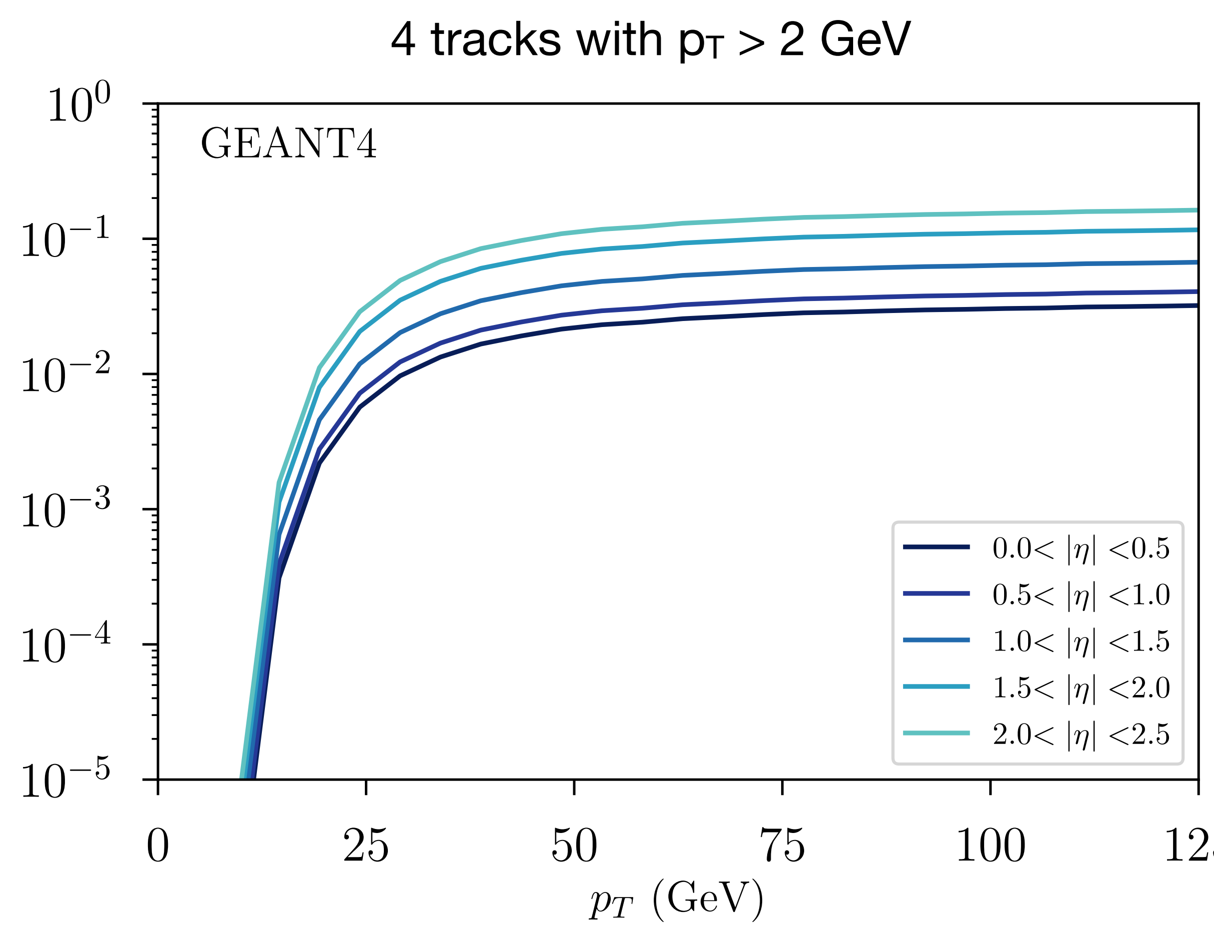
Must verify that this does not swamps the trigger bandwidth!

Interactions with detector material

Pion gun in GEANT4



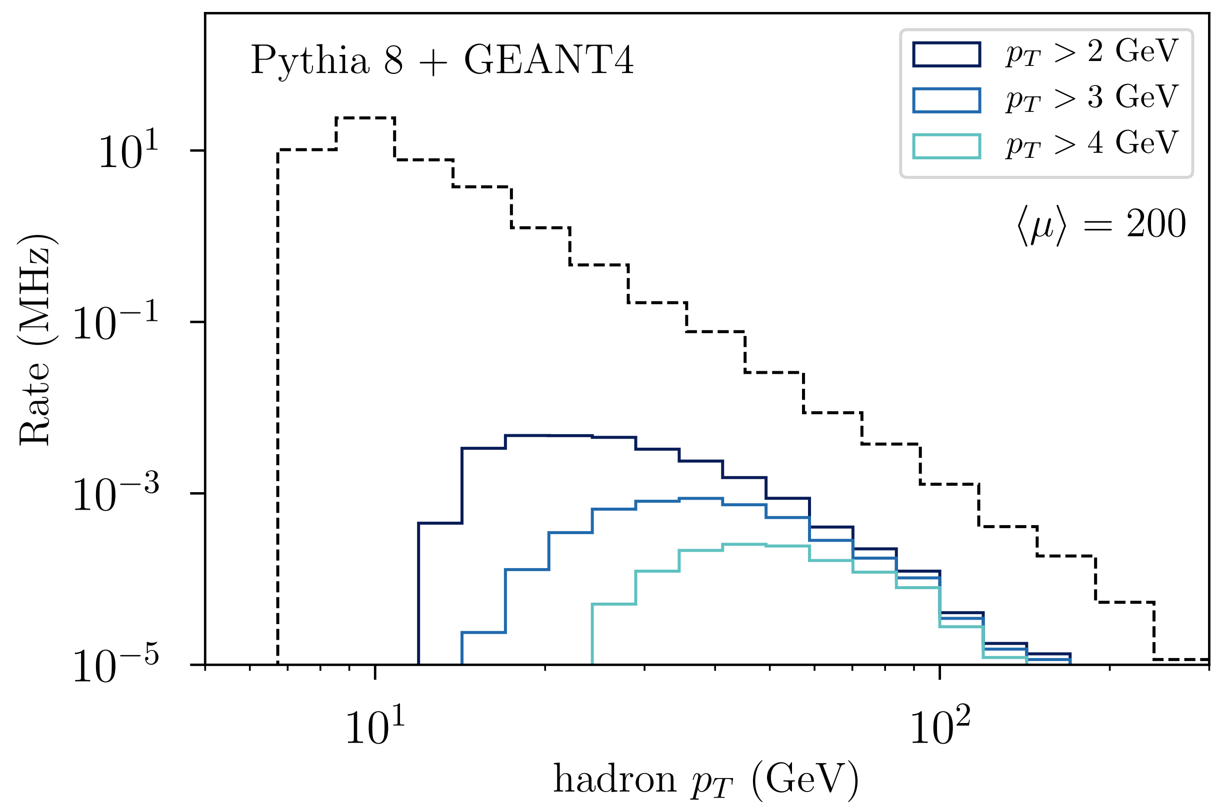




Y. Gerhstein, SK, D. Redigolo: arXiv 2012.07864

Interactions with detector material

Fold in particle production rate



Rate is likely manageable

Background rate summary:

Conservative assumptions:

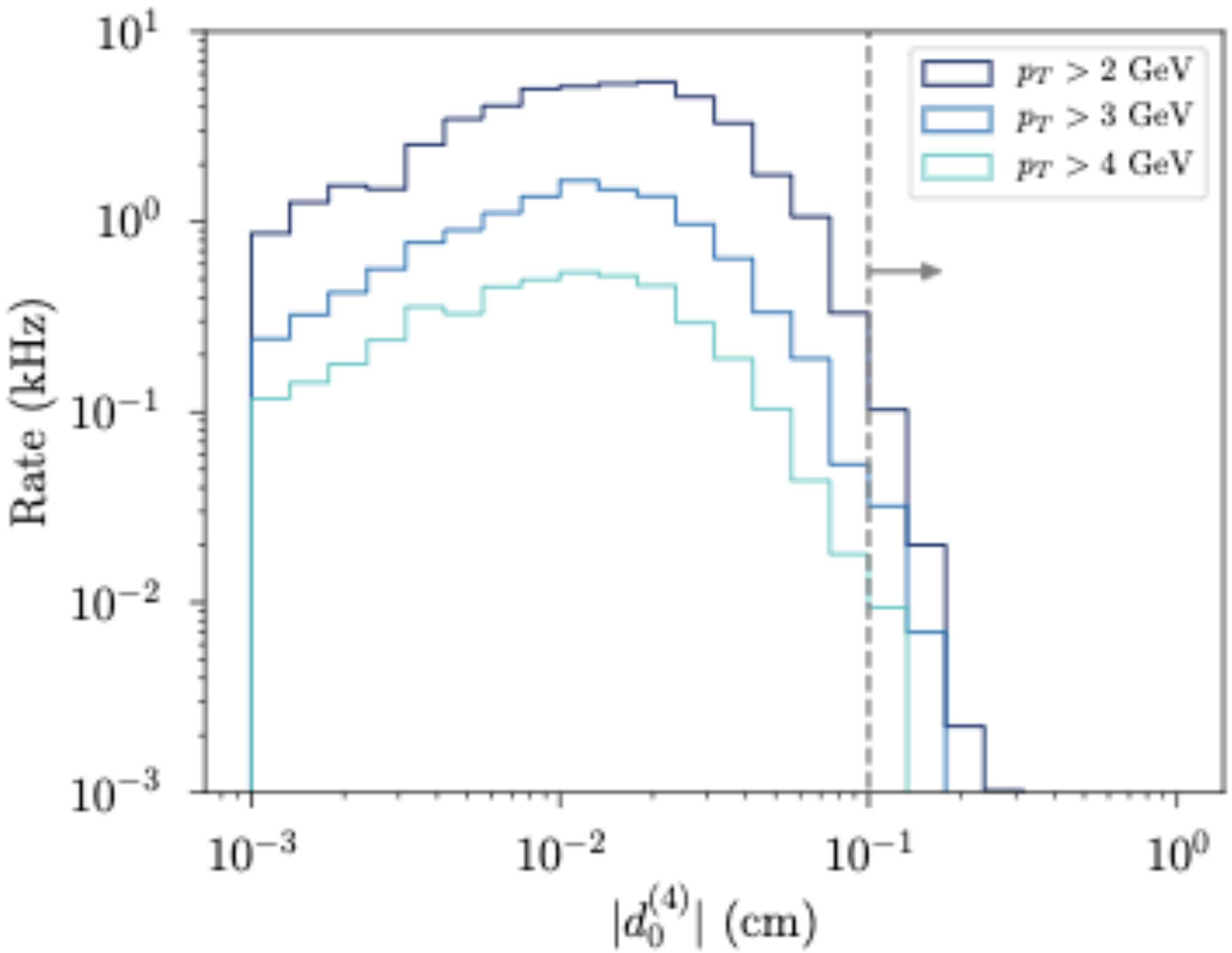
- Assu
- No n
- No is

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: arXiv 2012.07864

B meson background

Multi-track vertices from B decays



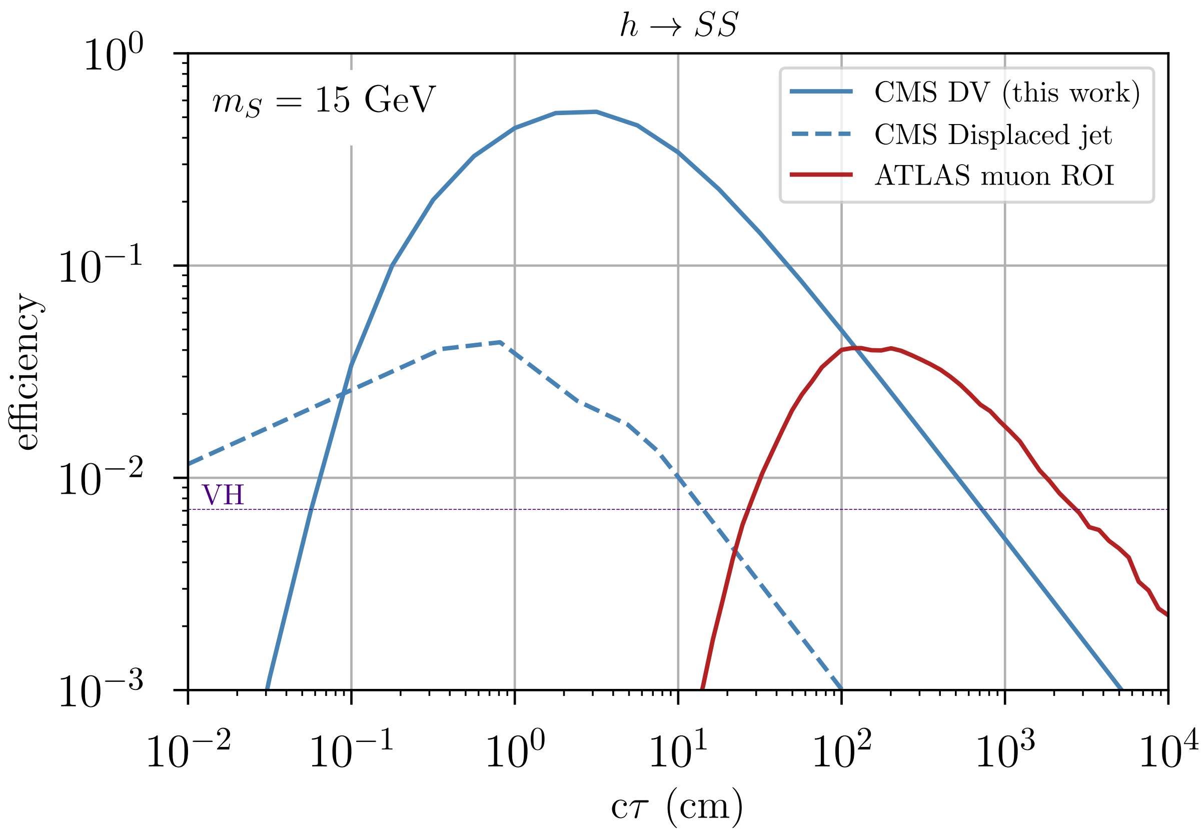
Efficiently removed with a d_0 cut

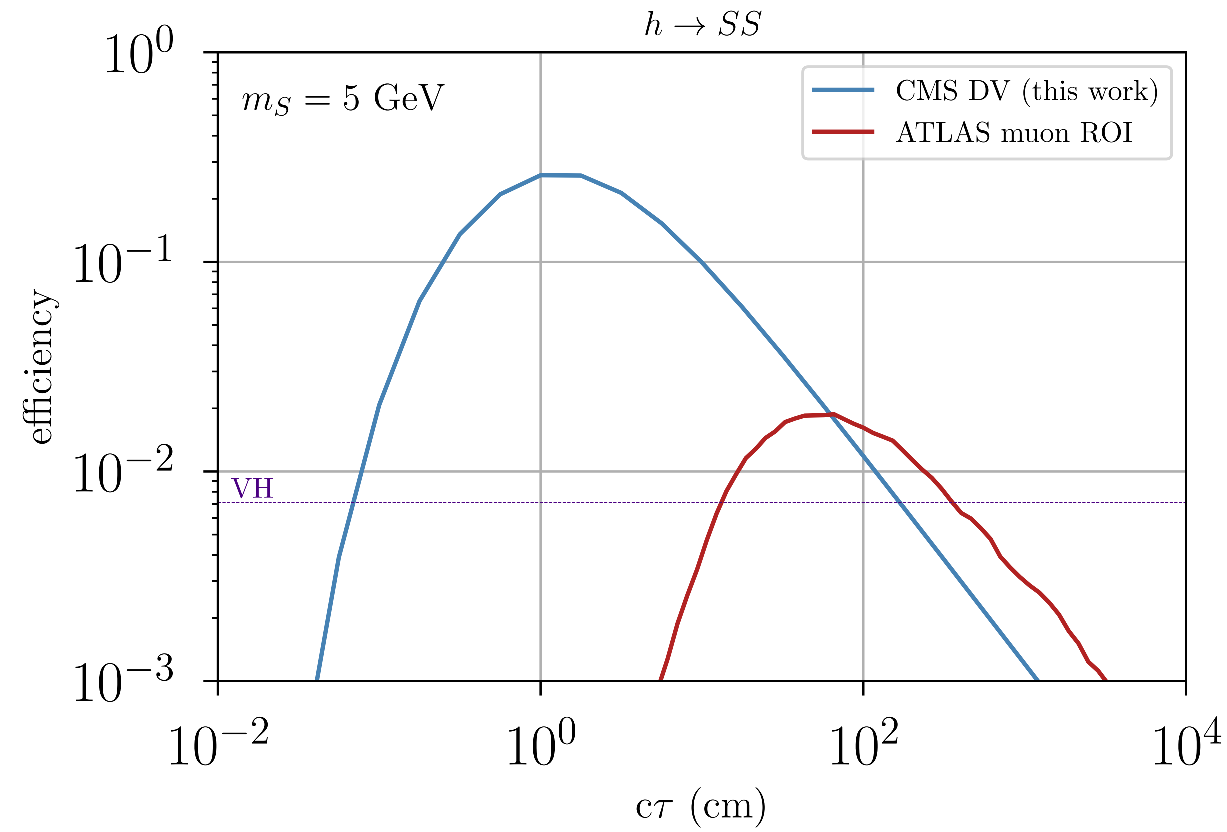
Y. Gershtein, SK, D. Redigolo: arXiv 2012.07864

Results

Example: $h \to SS$

$\hookrightarrow$ hadrons





Qualitative gain in sensitivity appears possible

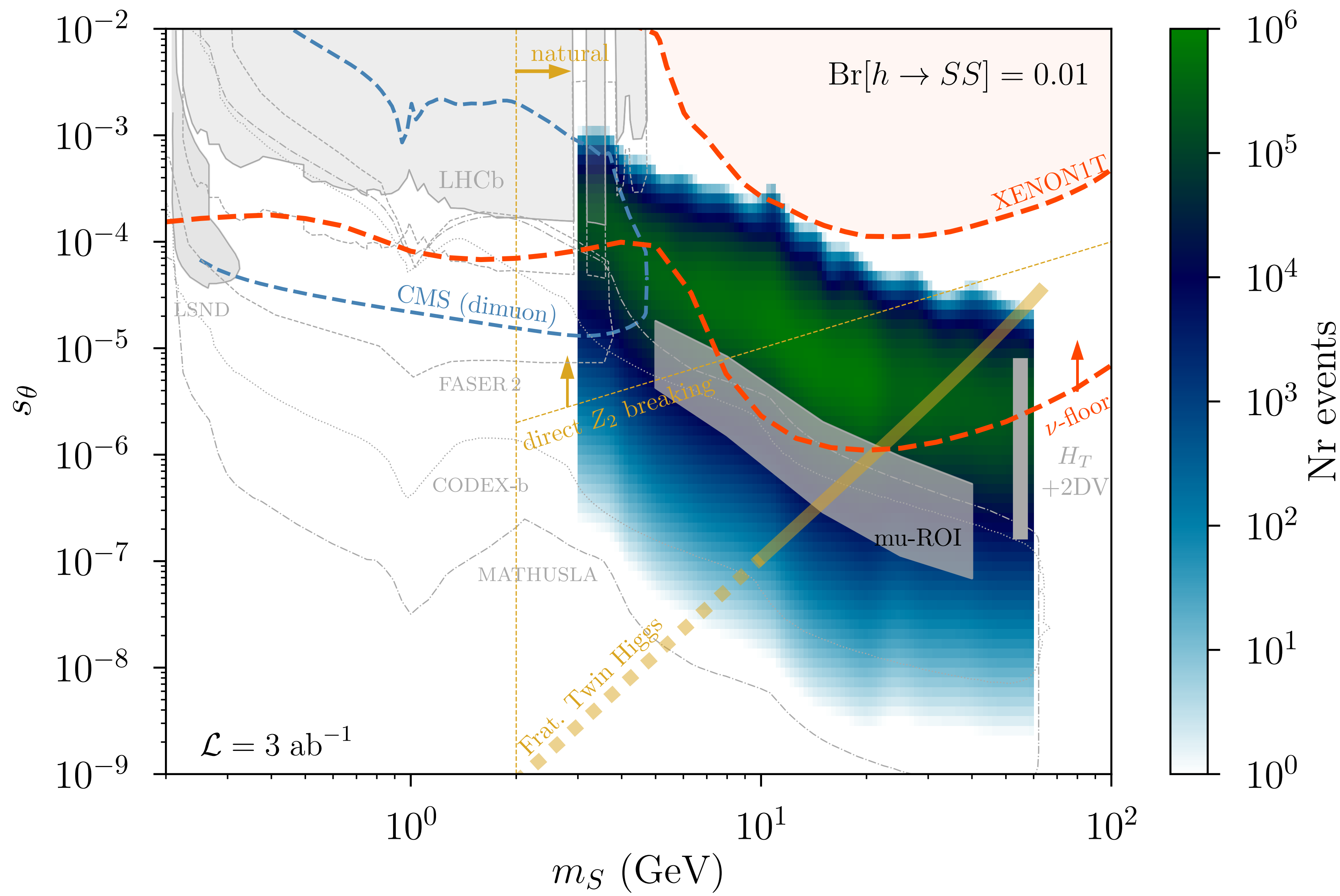
Y. Gerhstein, SK, D. Redigolo: arXiv 2012.07864
Y. Gershtein: arXiv 1705.04321, CMS PAS FTR-18-018
ATLAS muon ROI trigger: arXiv 1811.07370

Results

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

$h \to SS$

$\quad \hookrightarrow$ hadrons

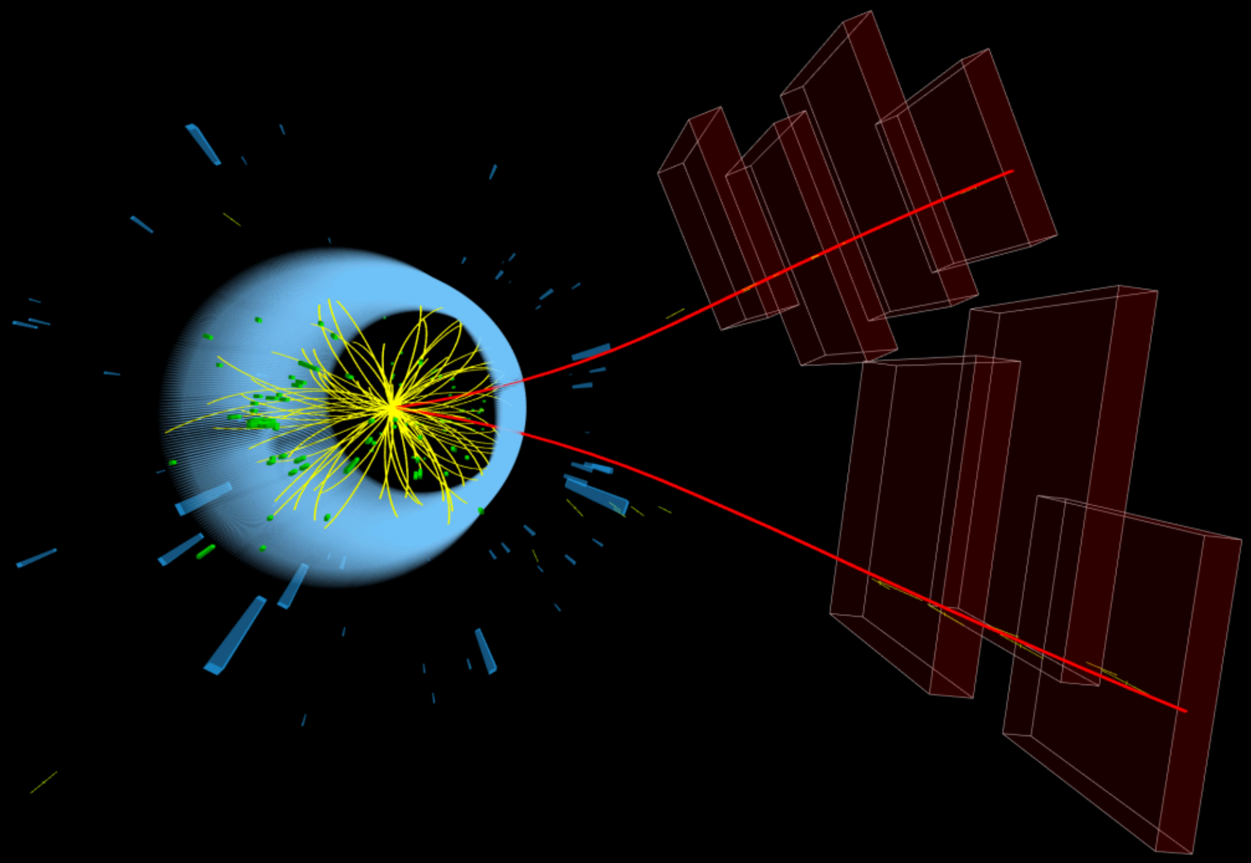


Applications to:

- SUSY
- composite higgs
- relaxion models
- neutral naturalness
- heavy axions
- dark matter
- baryogenesis
- …

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

Conclusion



The LHC is a Higgs & B factory…

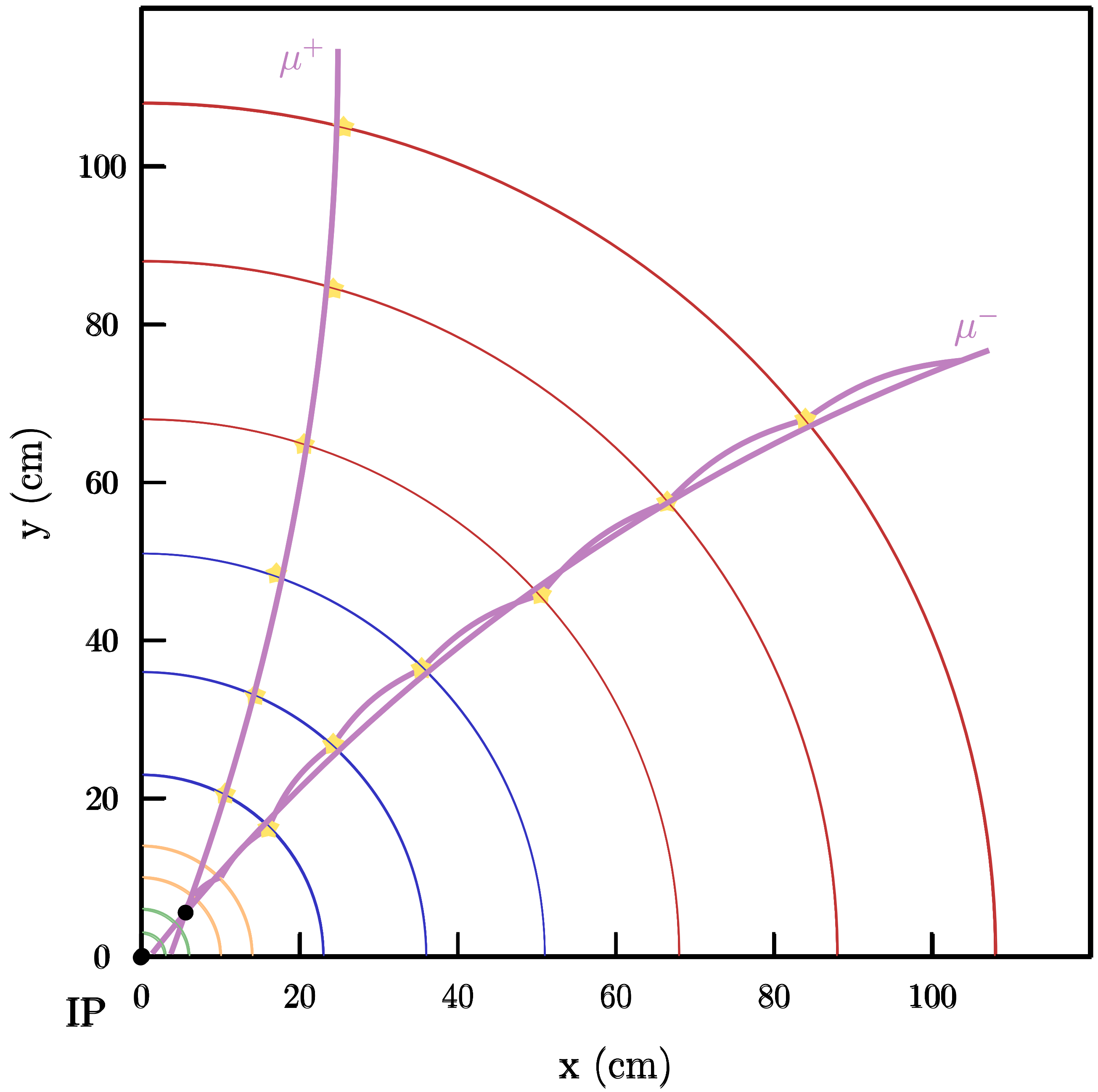
… Higgs and B decays are golden opportunities for beyond the Standard Model physics

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

… but we must be bold and continue to innovate!

Thank you!

Toy detector simulation

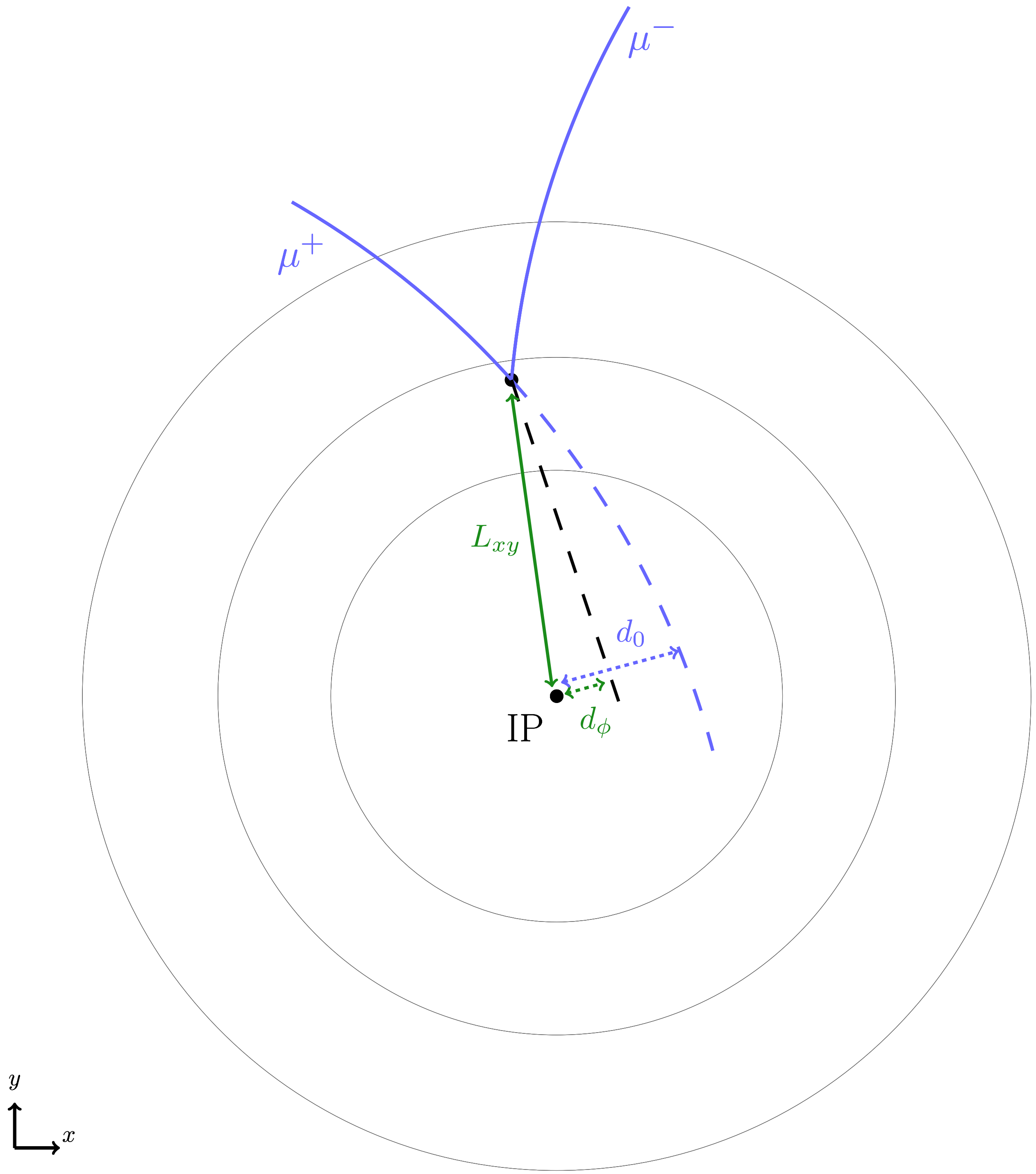


Procedure:

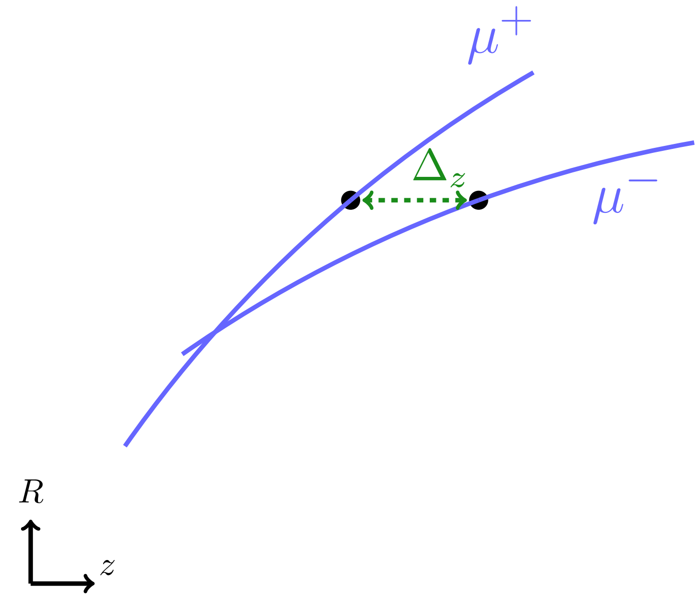
1. Propagate track
   (including multiple scattering)
2. Find the stubs
   (smearing for resolution)
3. Fit a helix to the stubs
   (require at least 5 stubs)
4. Reconstruct a vertex

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

Some notation



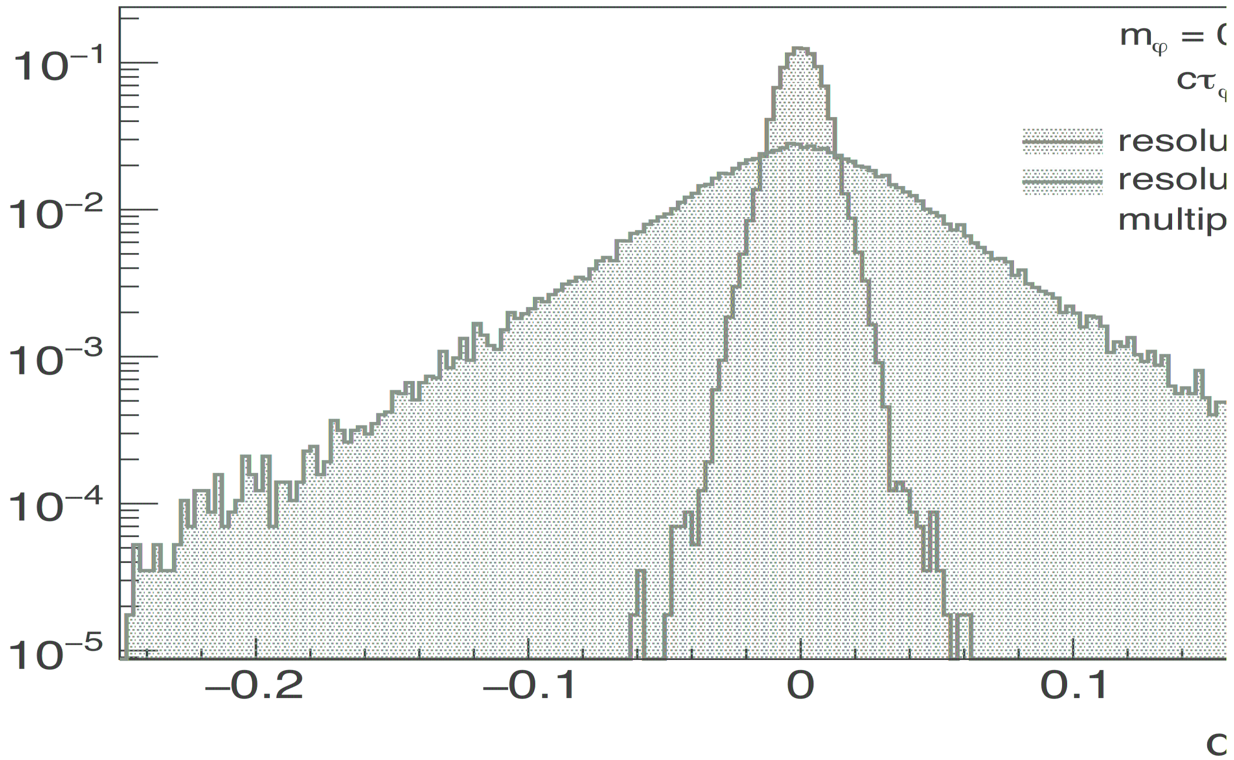
Vertex is never perfect:
Δ_z measures vertex quality



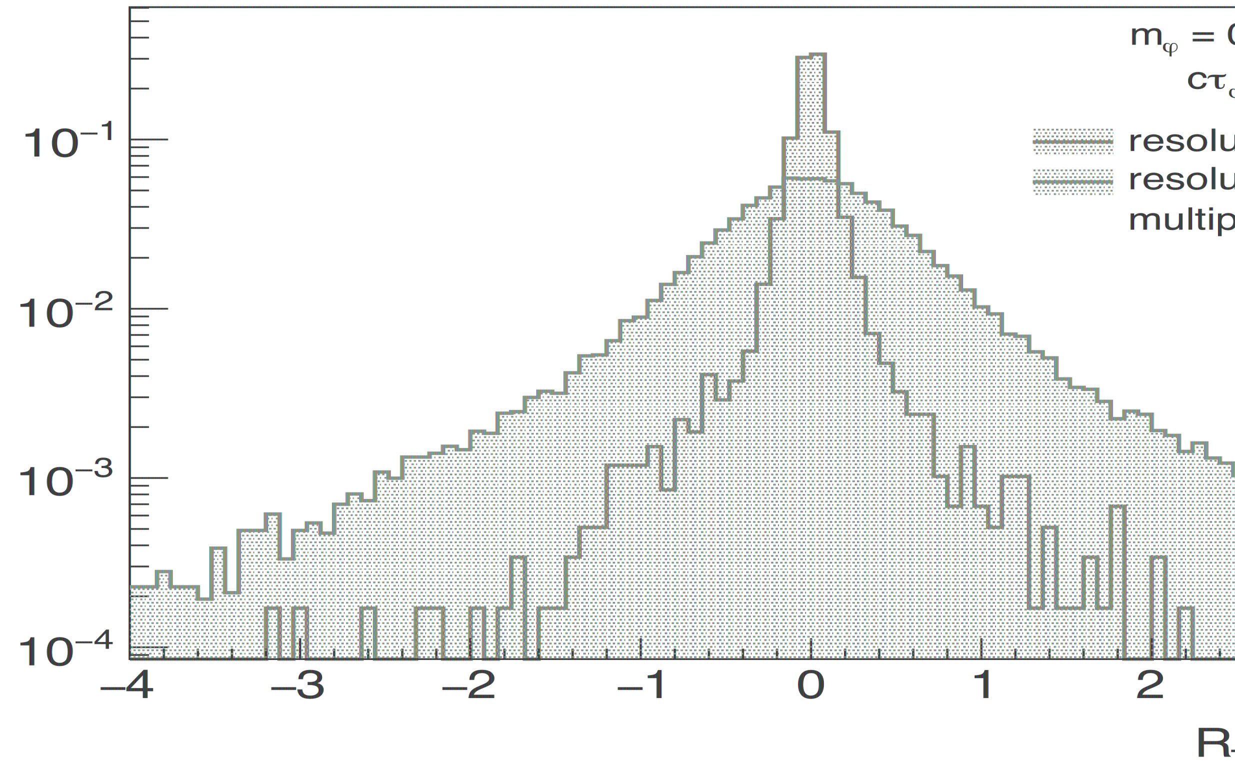
Y. Gershtein, SK: arXiv 1907.00007

Performance

Track impact parameter in transverse plane



Vertex distance in transverse plane



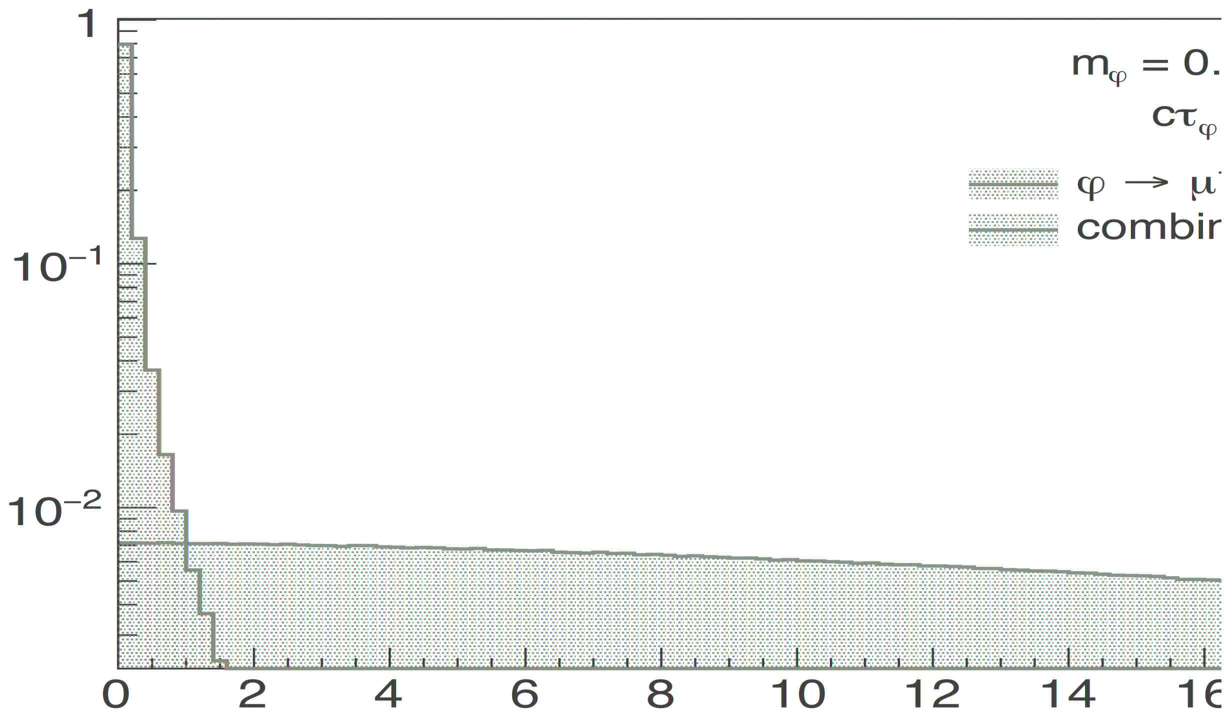
Fairly good resolution on d_0, resolution on vertex location is poor as expected.

Y. Gershtein, SK: arXiv 1907.00007

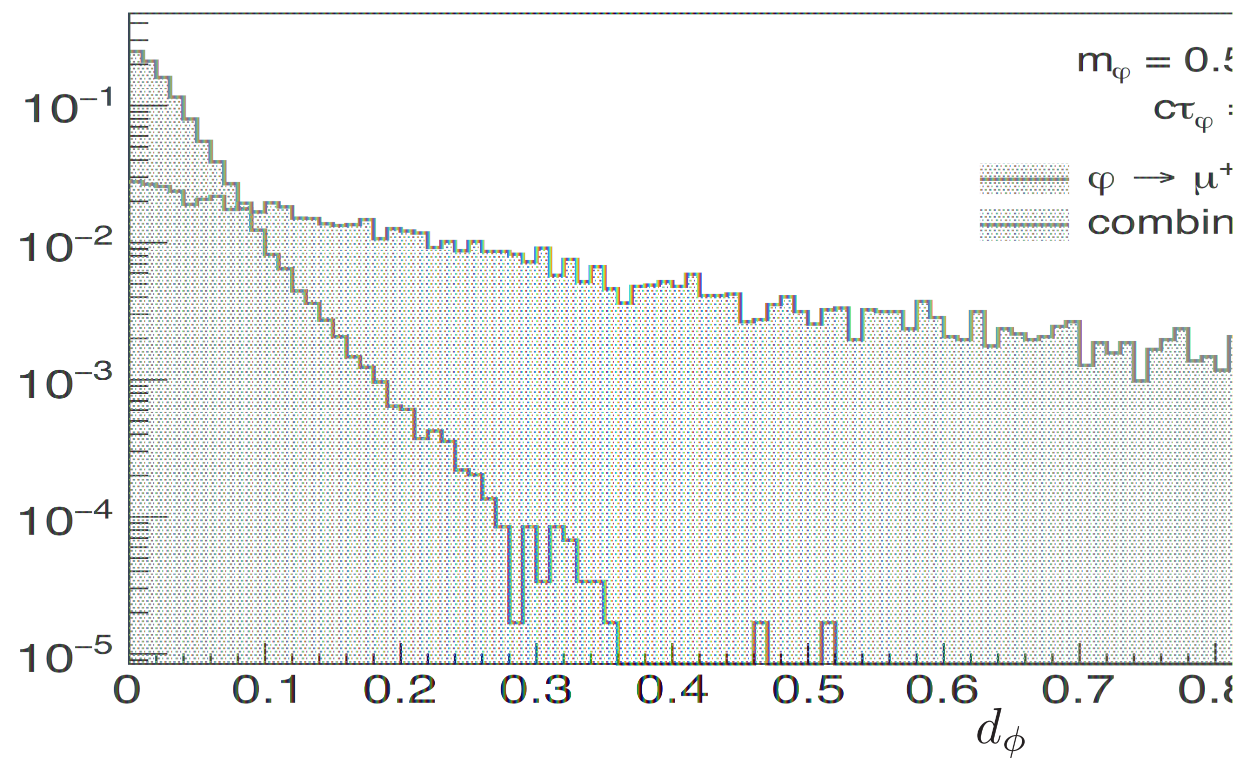
Fighting fakes

Assume 30 fake tracks per event → 225 fake "vertices" per event!

Distance between tracks in z-direction



Impact parameter of mother



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

↓

~ 10^{-2} suppression

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

↓

~ 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

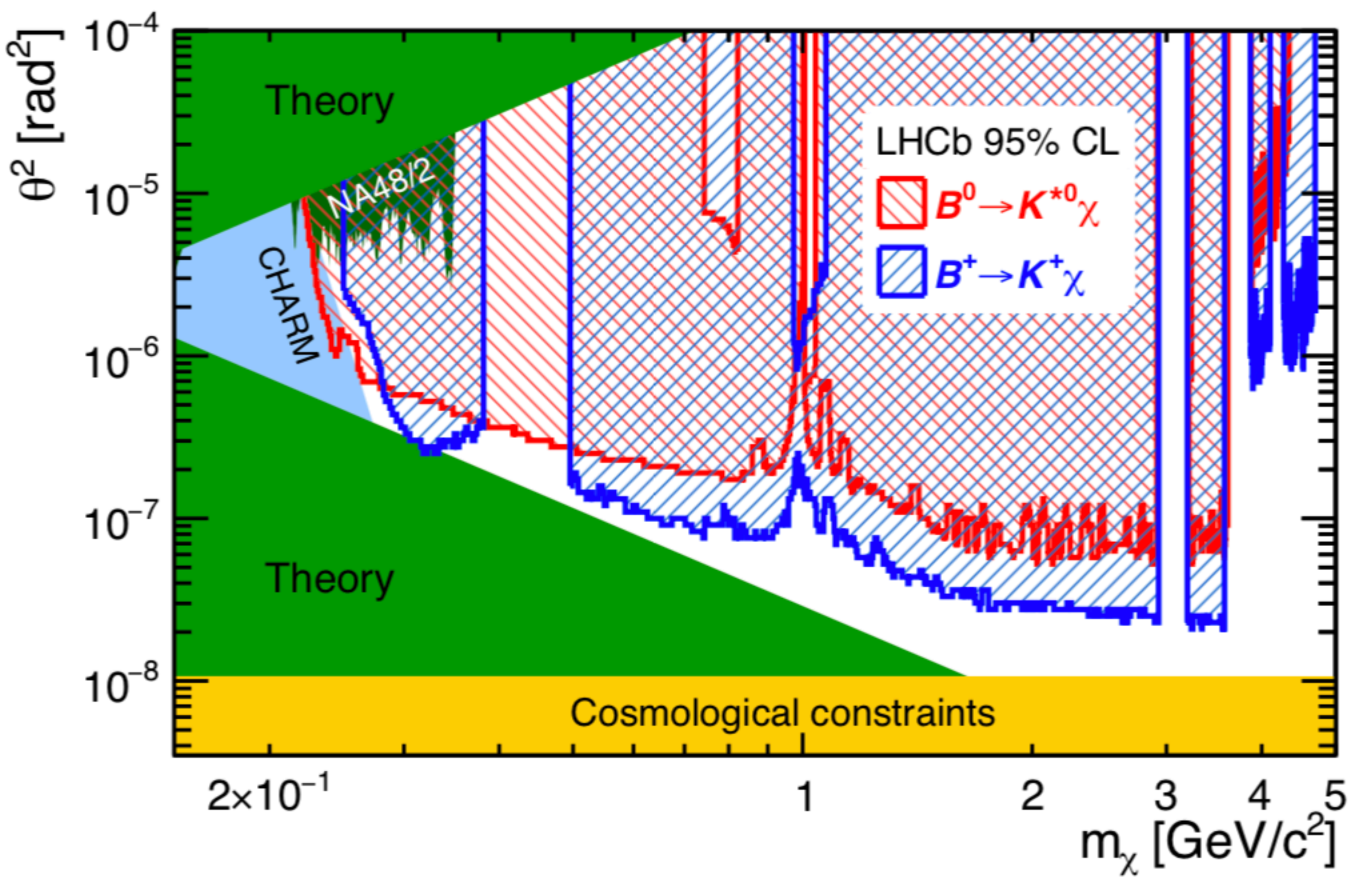
3 lifetime bins:

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

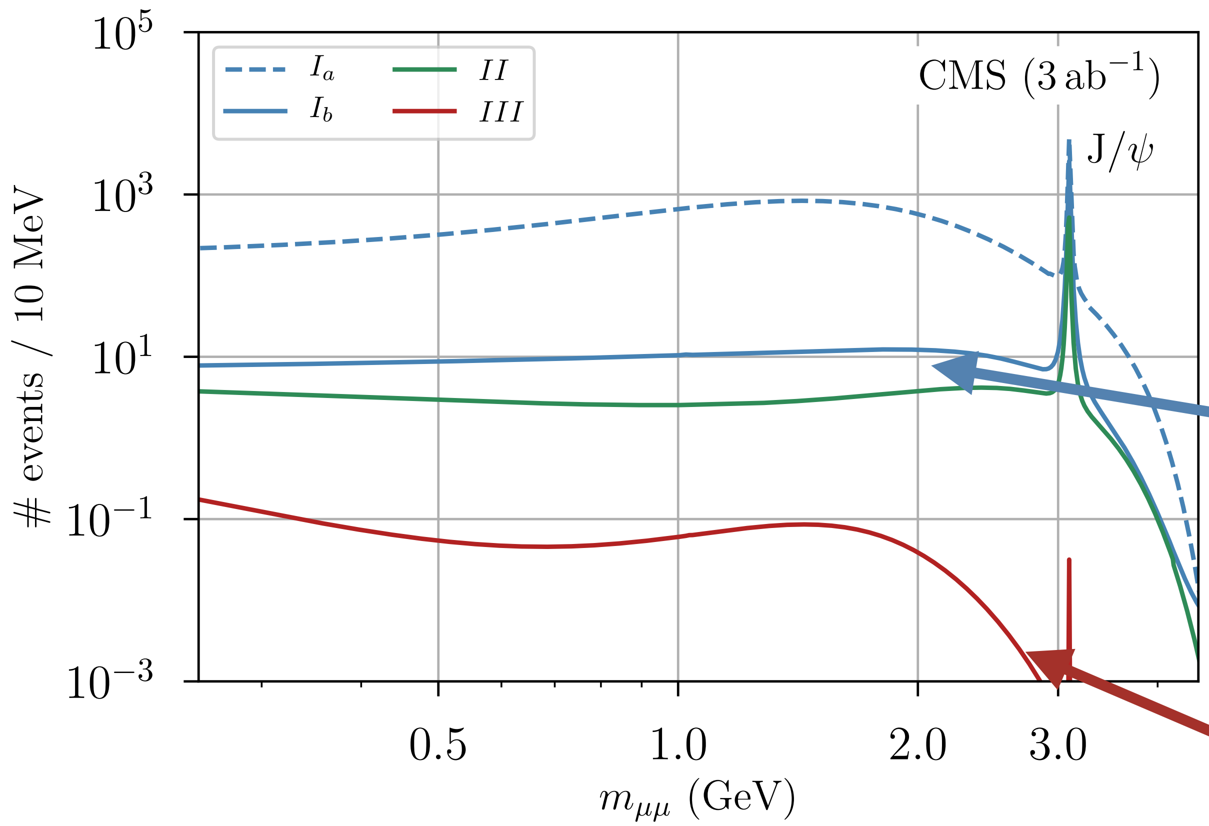


Offline analysis

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

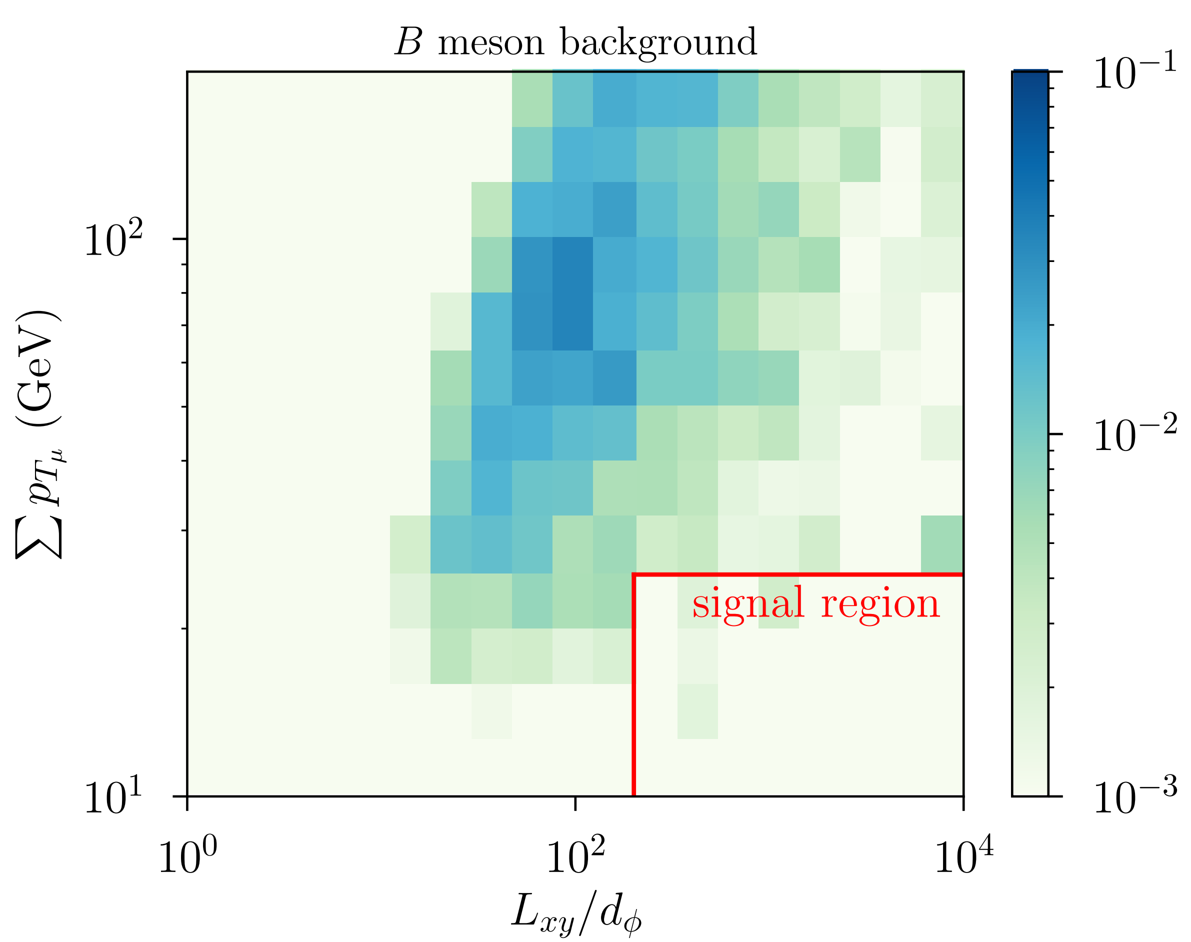
Additional cuts

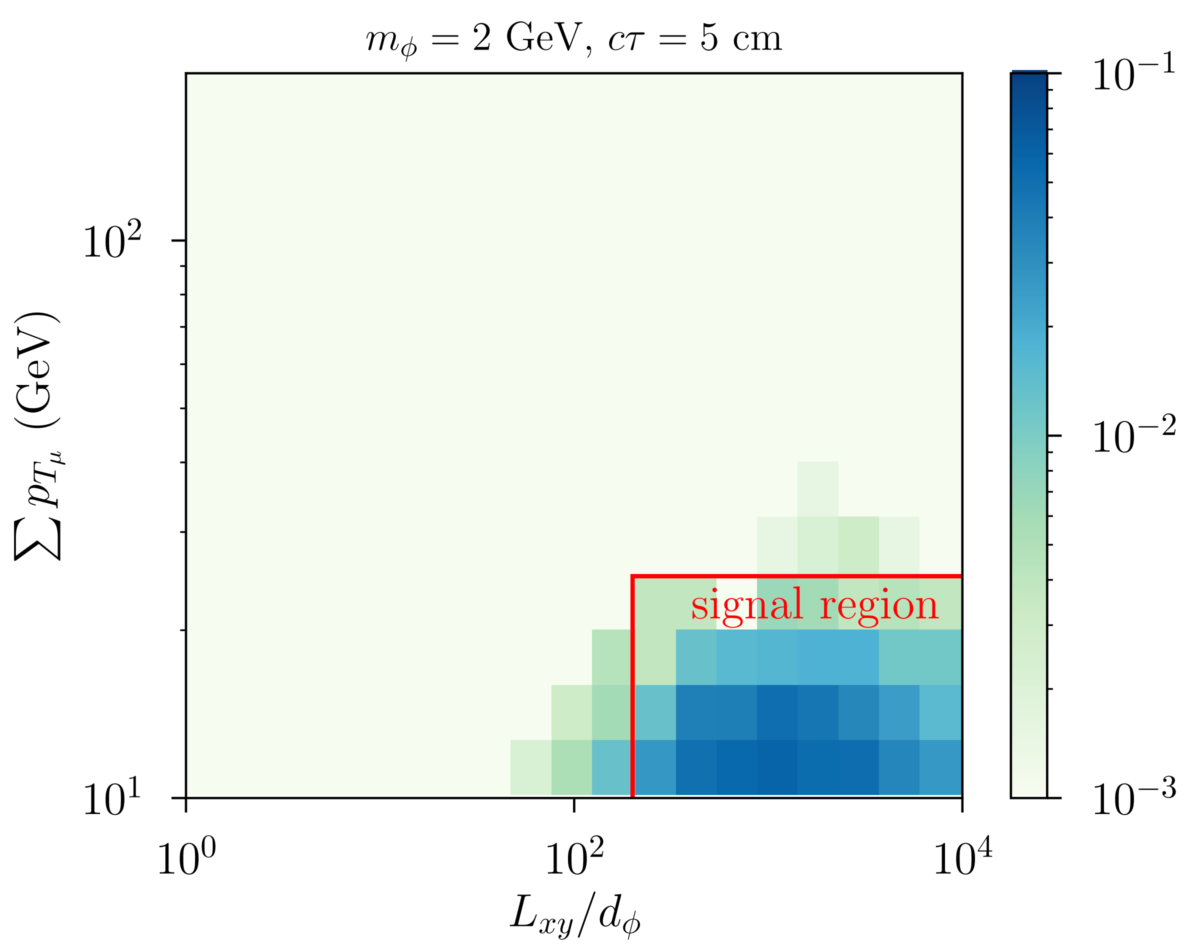
Main background from B-meson decays

<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

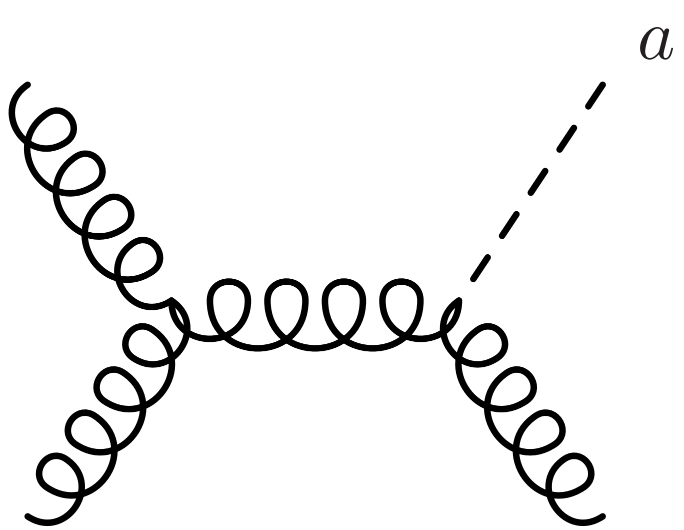


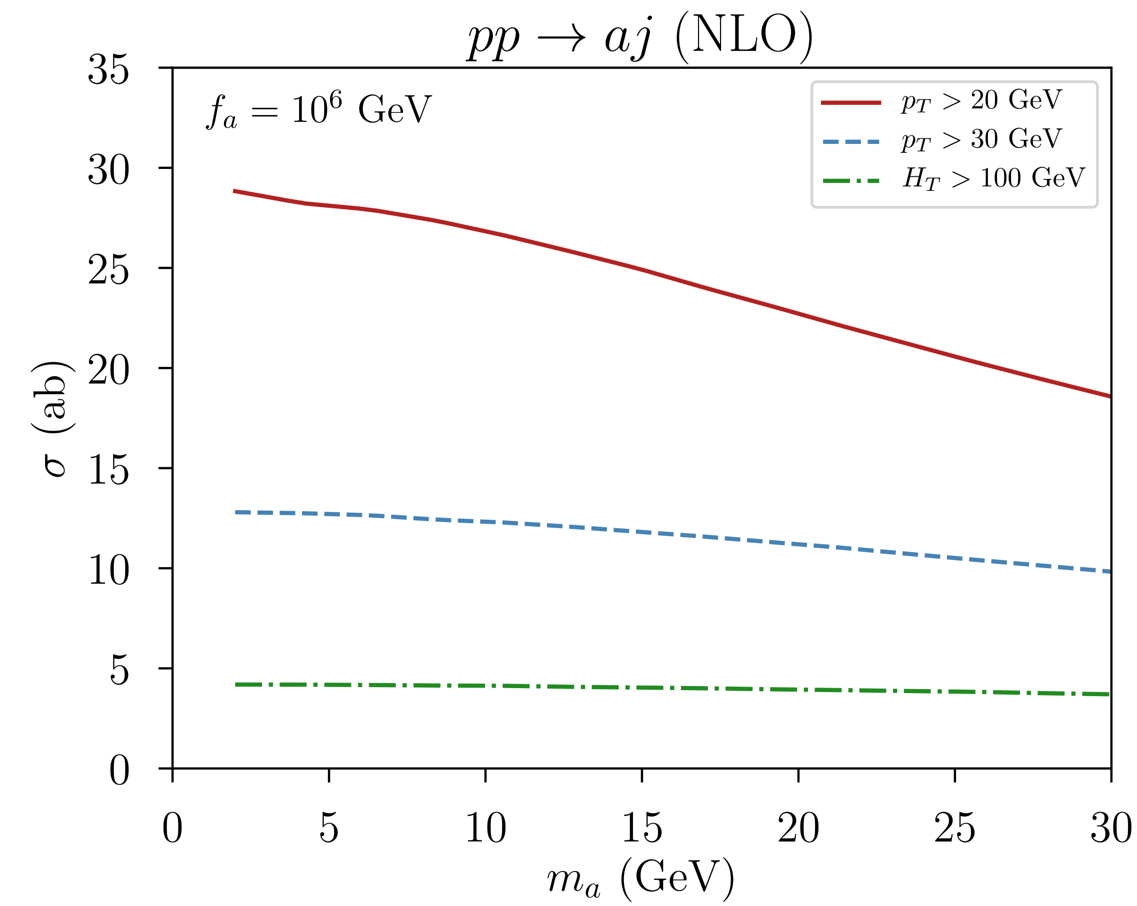


J. Evans, A. Gandrakota, SK, H. Routray: arXiv 2008.06918

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

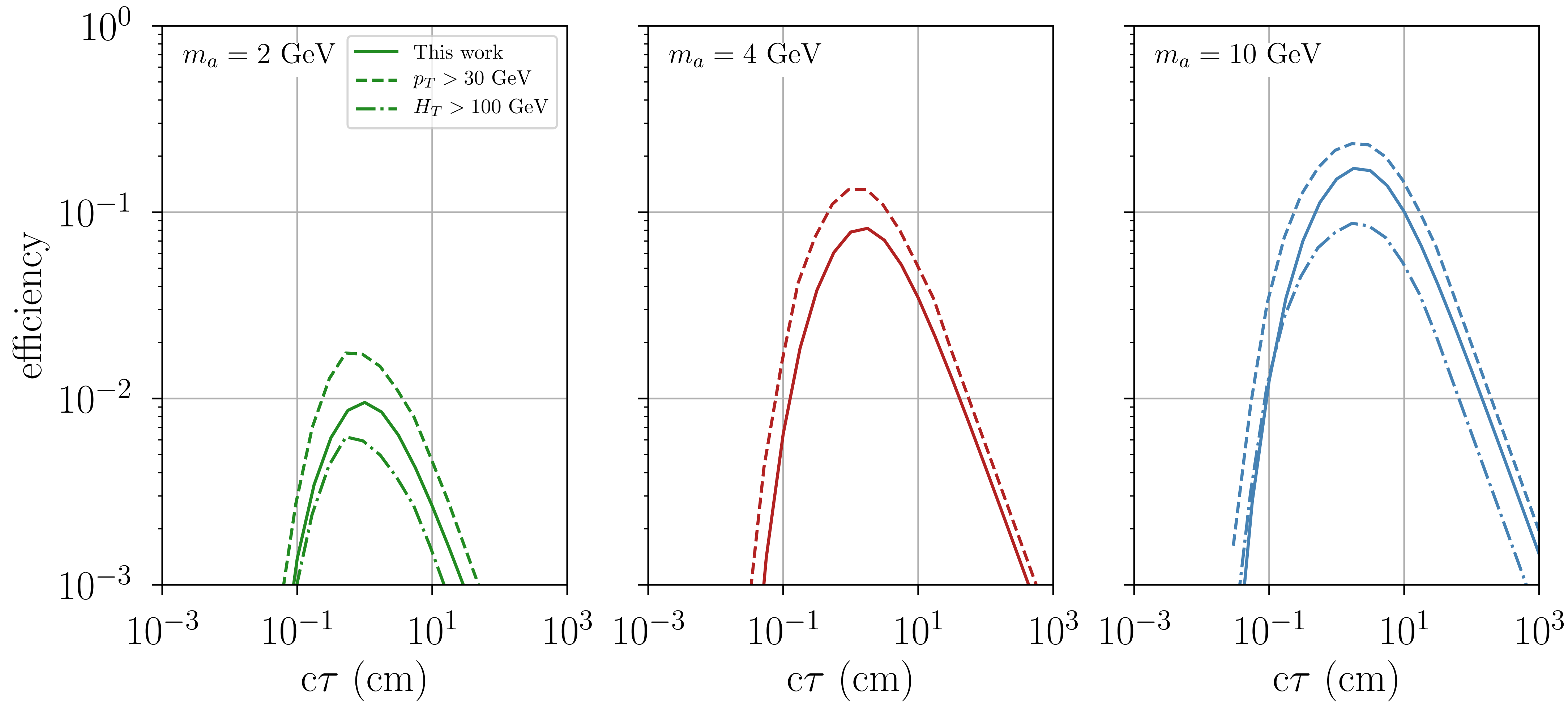
Lifetime:

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

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

Axion-like particle

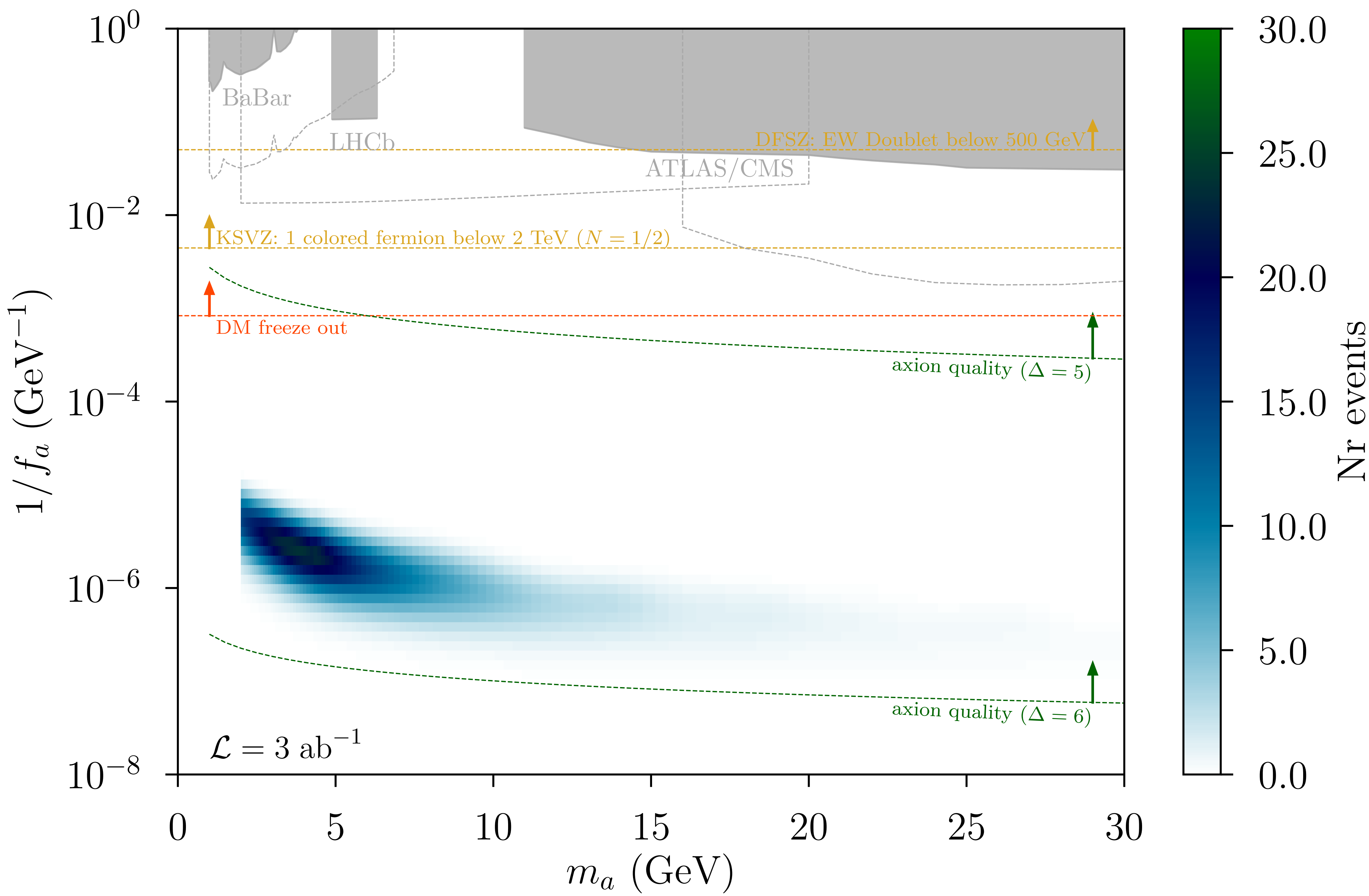
Efficiency:



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

Axion-like particle

Result:



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