Searching for long lived particles
Why & how?

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Thanks to S. Knapen, M. Papucci, D. Robinson, B. Dey for slides

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LPNHE PARIS

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RECEPT

Possibilities

&

Capabilities

Why long lived particle searches?

Long lifetimes arise from a hierarchy of scales or a small coupling*

Three mechanisms:

- Off-shell decay
- Small splitting (phase space)
- Small coupling

Lessons from the SM:

- generic if there is more than one scale
- Often 3 body decays
- Weak theory prior on lifetime

(e.g. proton decay!)

small coupling

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

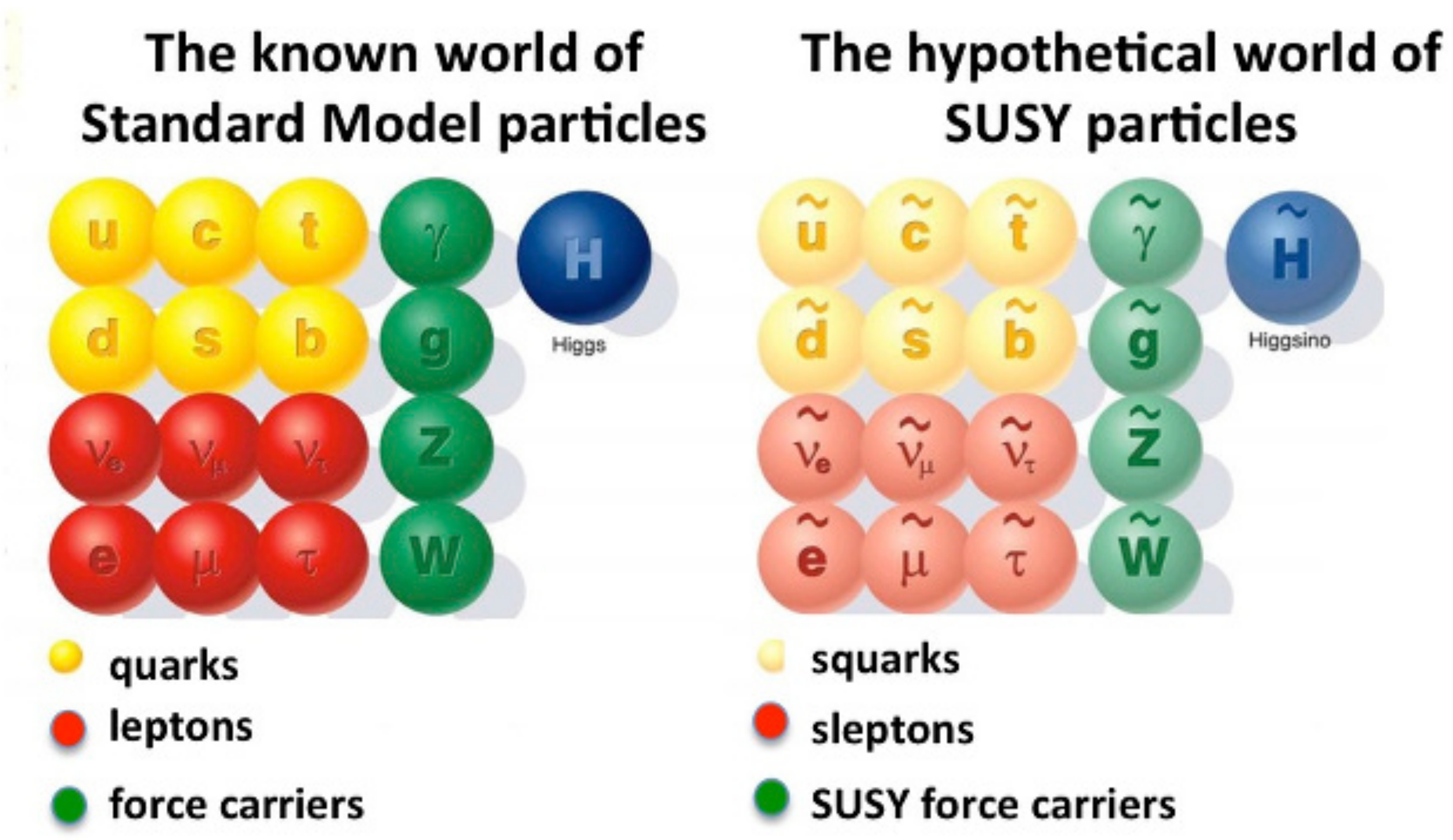
Set by symmetry structure,

typically n ≥ 4

hierarchy of scales

* could either be a hierarchy or loop suppression

Long-lived particles are generic



Other

R-parity violation
Gauge mediation
(mini-)split SUSY
stealth SUSY

Asymmetric Dark Matter
Freeze-in
composite Dark Matter
…

Baryogenesis
Neutrino masses
Neutral Naturalness
Hidden Valleys

A very wide range of BSM models introduce long-lived particles

LLP mass vs lifetime vs production

broken sym
weak mixing/ marginal operator
technically natural

$m \ll M$, typically $n \geq 4$
loop factors

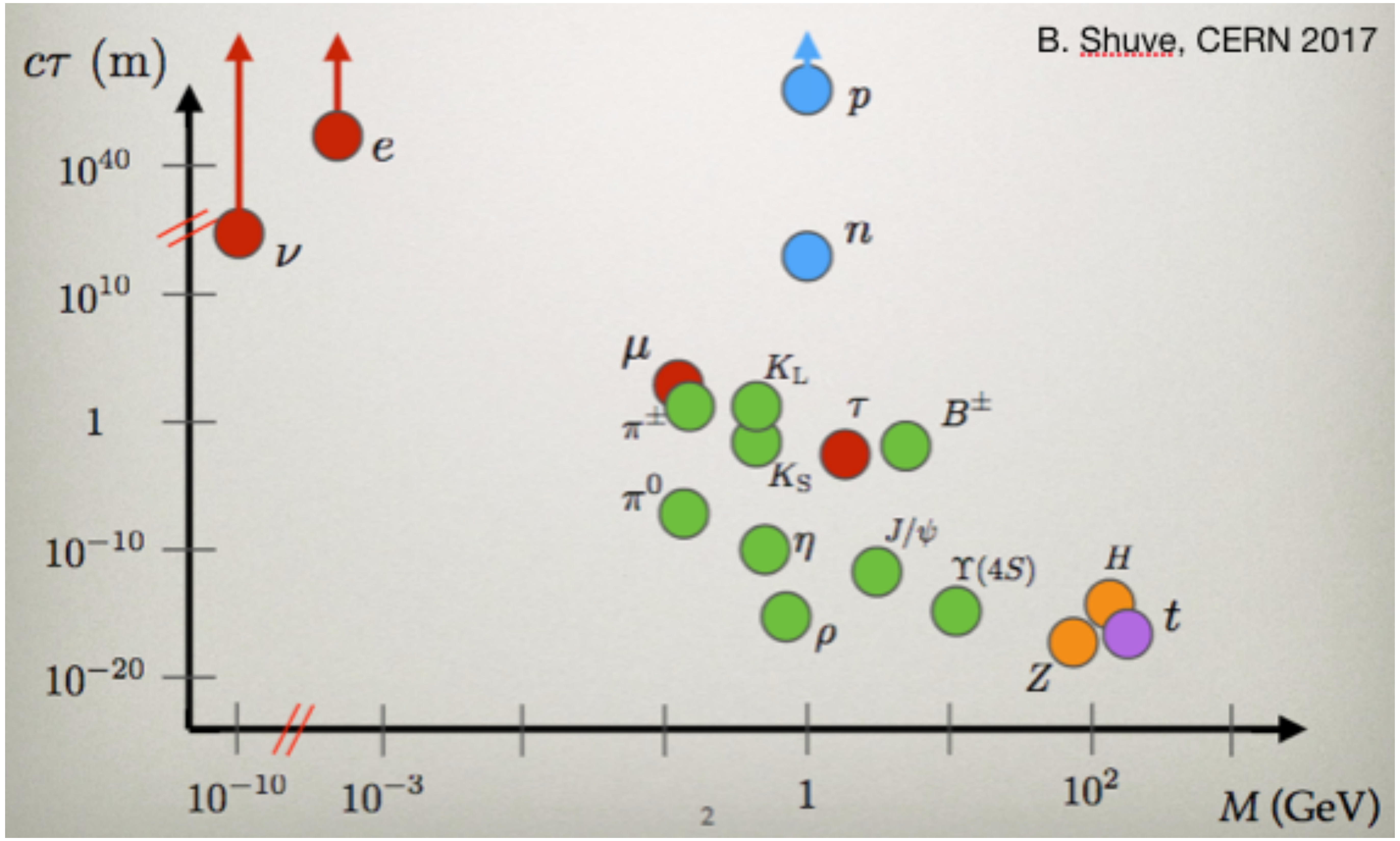
$$\Gamma \sim \varepsilon^2 \left(\frac{m}{M}\right)^n \mathrm{PS}$$

squeezed spectra
approx sym
multibody decays

The bigger the mass, the smaller in general the coupling you have to impose to get a narrow width (long lifetime)

The details linking production and decay in this heavily depend on the specific LLP and the portal used to access it.

LLP mass vs lifetime vs production



The bigger the mass, the smaller in general the coupling you have to impose to get a narrow width (long lifetime)

The details linking production and decay in this heavily depend on the specific LLP and the portal used to access it.

So how do we search for them?

No theory guidance on lifetime → large detectors

Many possible decay modes → hermeticity, particle ID

Small coupling and production rate → zero background

Small coupling and production rate → huge integrated lumi

Very hard for any single detector to meet all these criteria!

Collider vs. fixed target mode

	Fixed target	Collider
Advantages		
Disadvantages		

Collider vs. fixed target mode

	Fixed target	Collider
Advantages	Production rate Collimated production & decay	
Disadvantages		

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Collider vs. fixed target mode

	Fixed target	Collider
Advantages	Production rate Collimated production & decay	Access to higher mass LLPs via e.g. Higgs portal
Disadvantages	No access to very heavy LLPs Big shielding required for bkg	Uncollimated production Hard to instrument Hard to shield

Collider vs. fixed target mode

To put the production argument in some context, consider the SPS vs. HL-LHC, each over 5 years

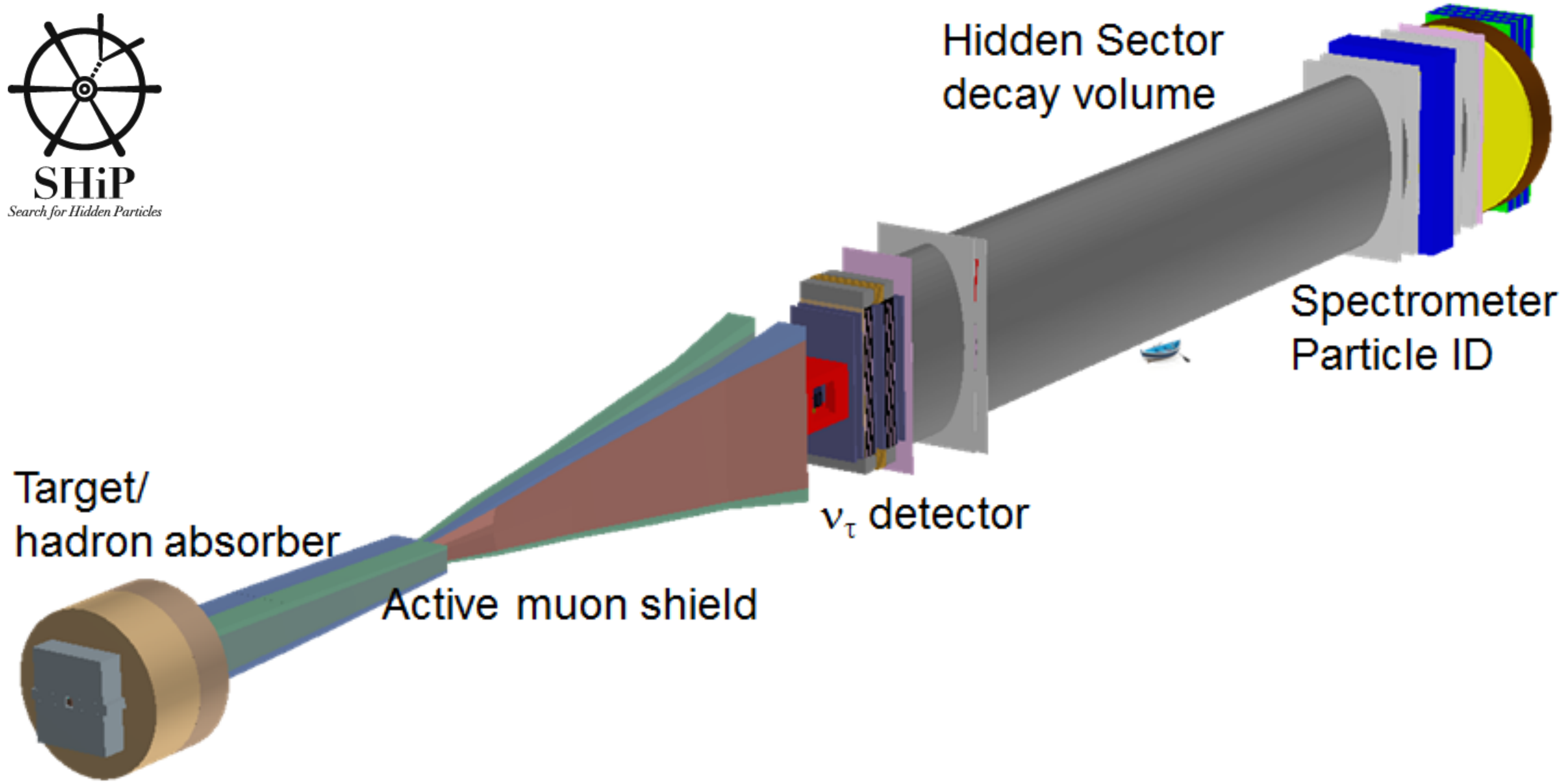
Charm Hadrons @ SPS : $O(10^{18})$
Charm Hadrons @ HL-LHC : $O(10^{16})$

Beauty Hadrons @ SPS : $O(10^{14})$
Beauty Hadrons @ HL-LHC : $O(10^{15})$

This is why SHIP is so great at LLPs produced in charm decays, while HL-LHC can compete for beauty and dominates for anything heavier

Distance versus solid angle coverage

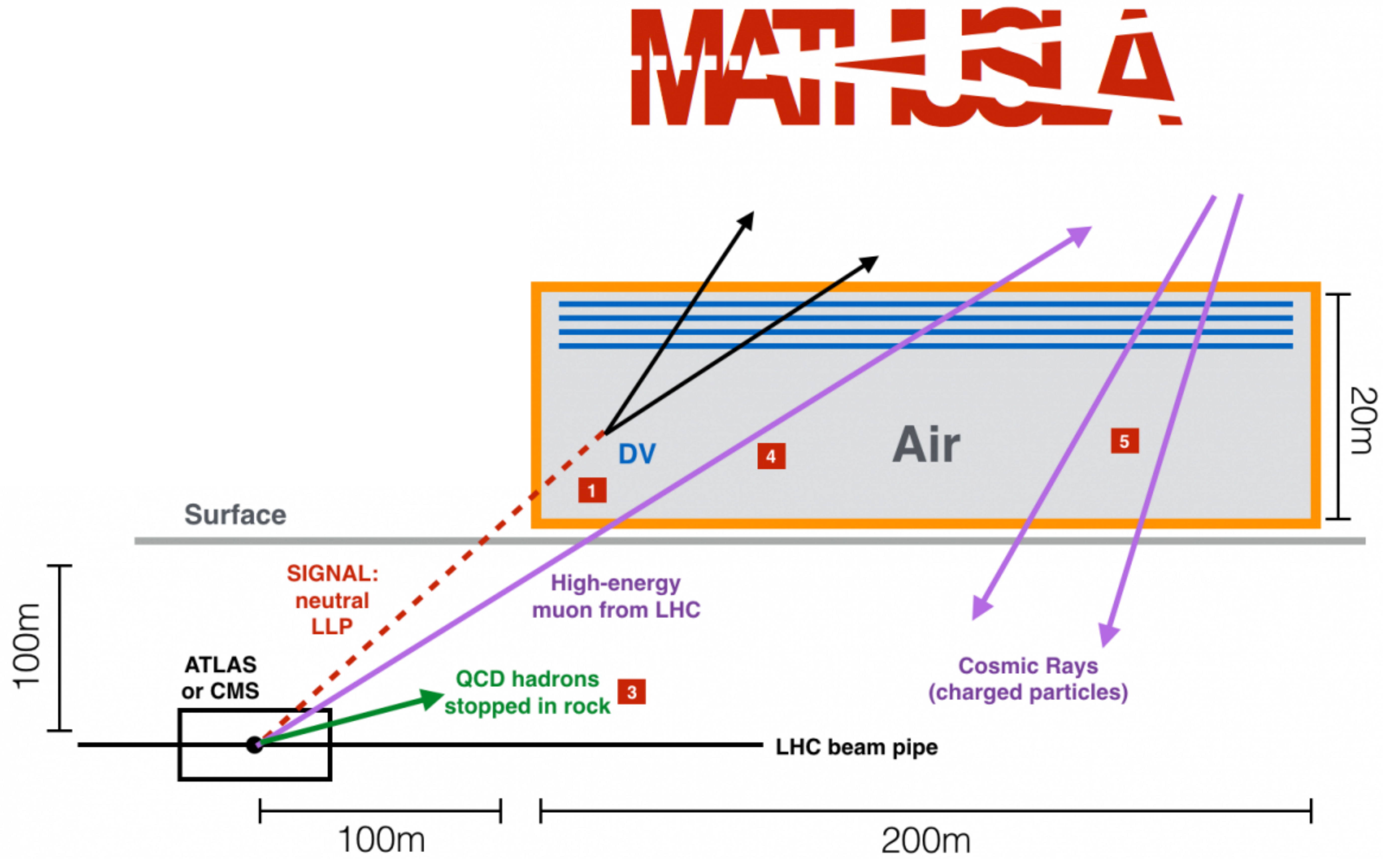
Fixed target : collimated production



Collimated production and decay mean that solid angle coverage is largely independent of optimal decay volume. The geometry is dominated more by the required size of shield.

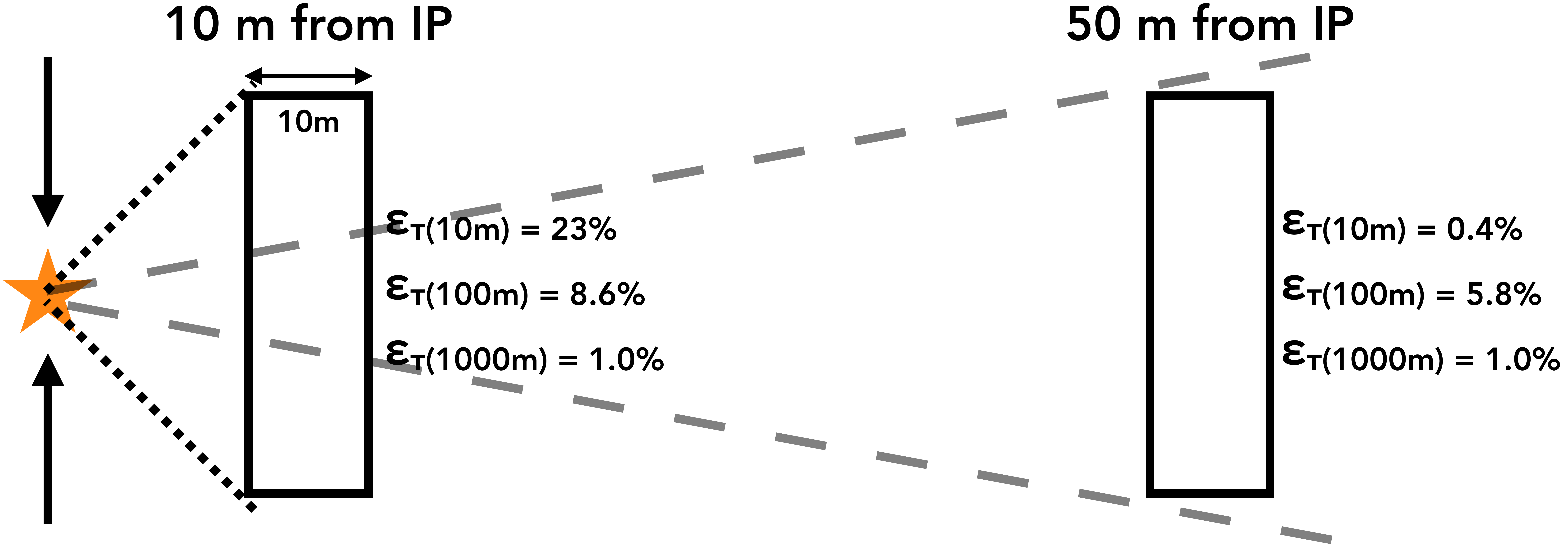
Distance versus solid angle coverage

Collider mode : solid angle is critical!



Uncollimated production means that unless you go forward like FASER, the size of your detector goes quadratically with the distance from collision point. Hence MATHUSLA's 200x200 m^2…

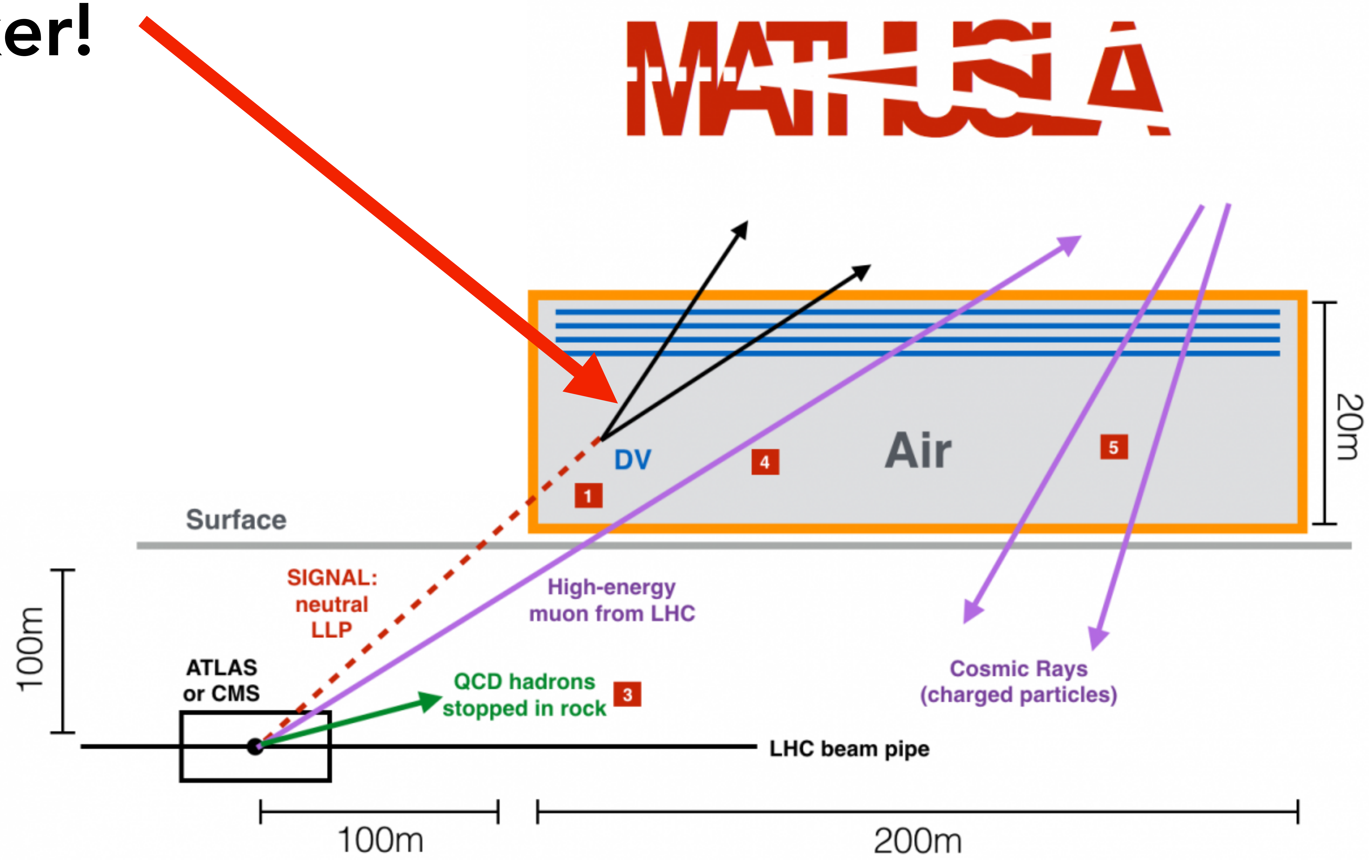
Distance versus lifetime coverage



Being far away isn't even really helpful for probing longer lifetimes, since for very long lifetimes the exponential looks almost flat anyway. What really matters is your volume/lumi. Of course if you see a signal, you'll struggle to measure its lifetime without a deep detector or precise timing…

Side effects of that kind of size

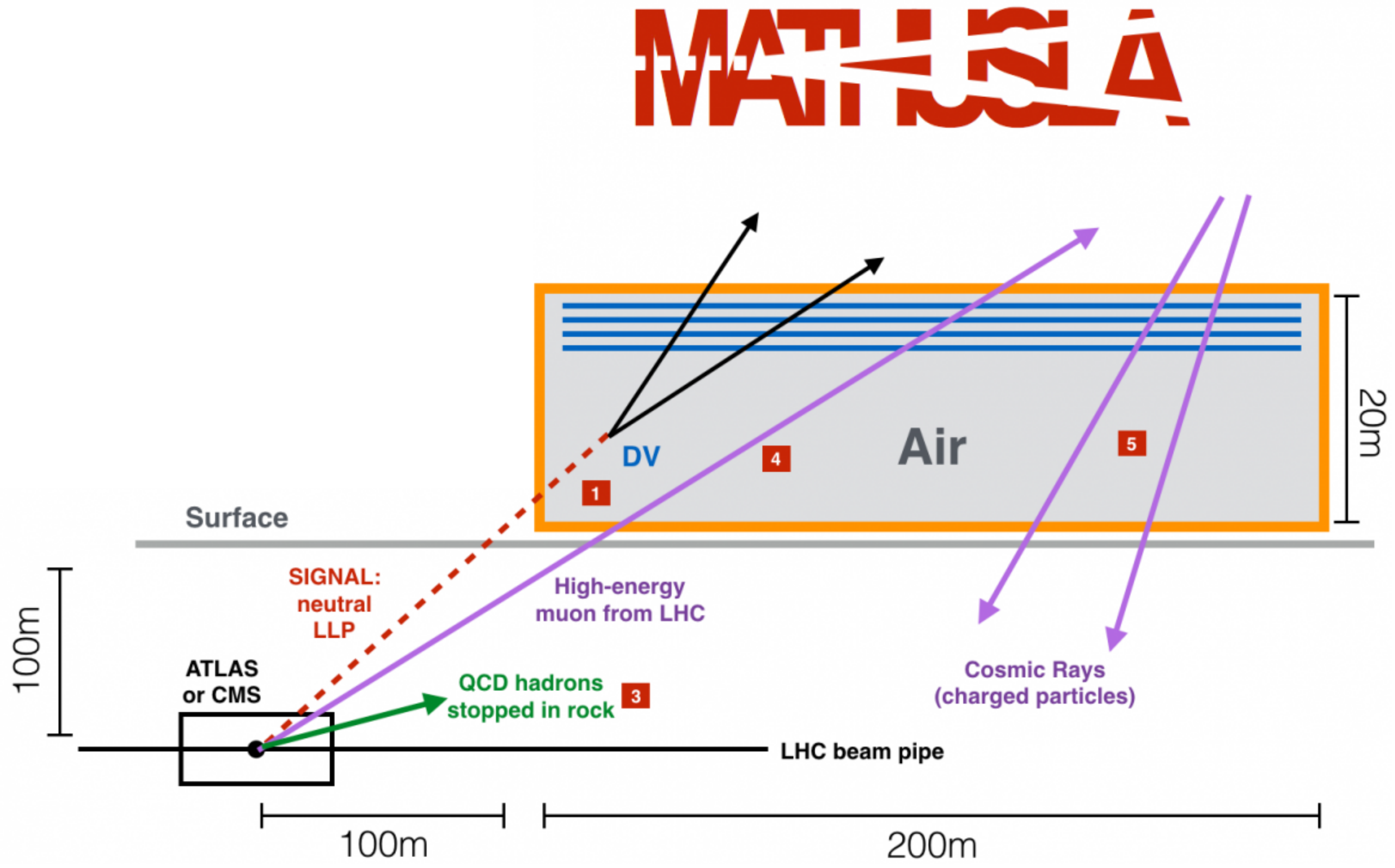
Huge distance to first measured point inside tracker!



This also has an interesting impact on your vertex resolution, which is shared by the fixed-target layout. Prepare to have distances of closest approach O(cm) for your signal products…

A kingdom for a magnet

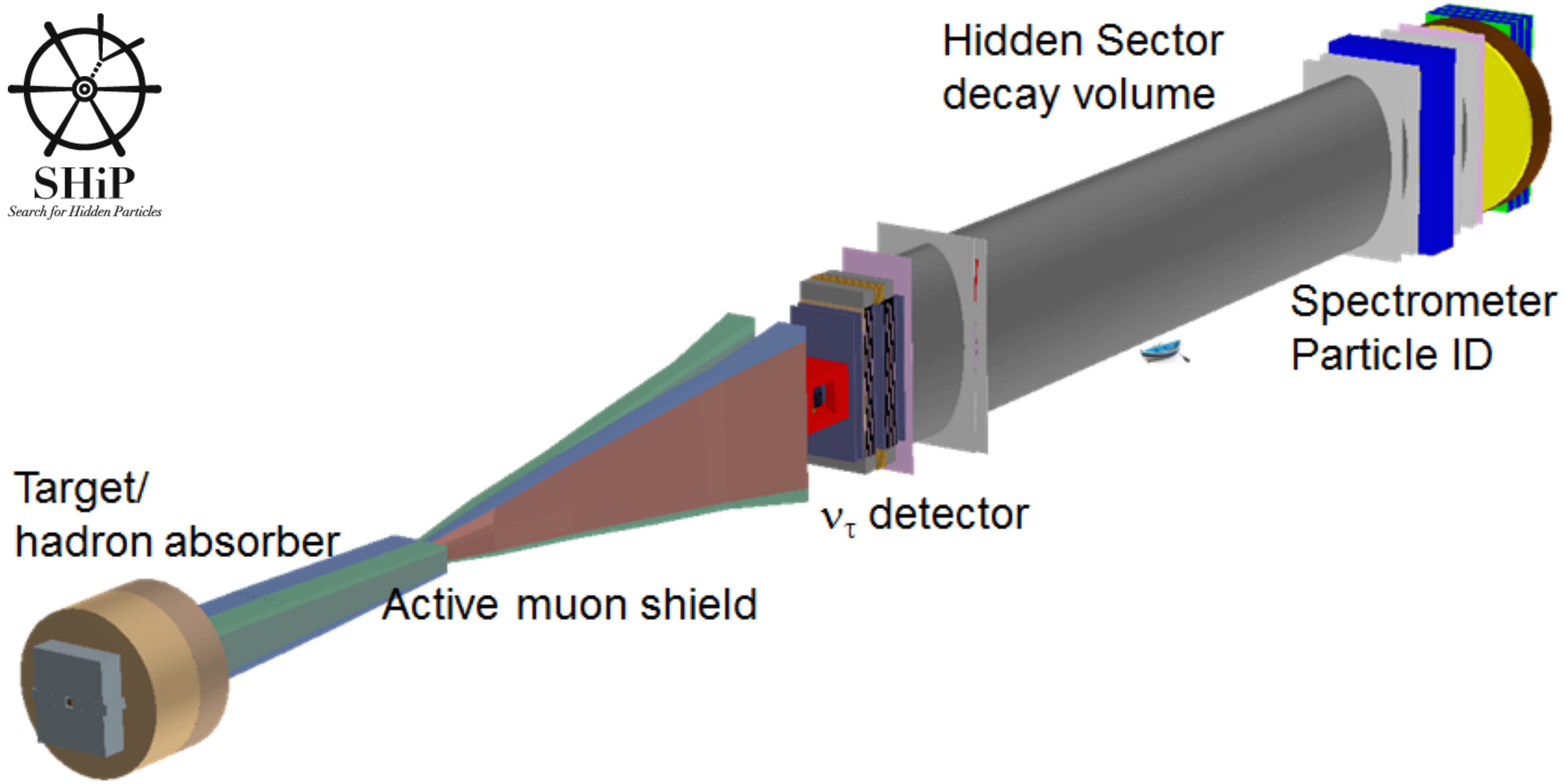
Collider mode : good luck…



The other problem with uncollimated production is that unless you want to do something crazy with permanent magnets, you are not really going to be able to install one to cover the volume

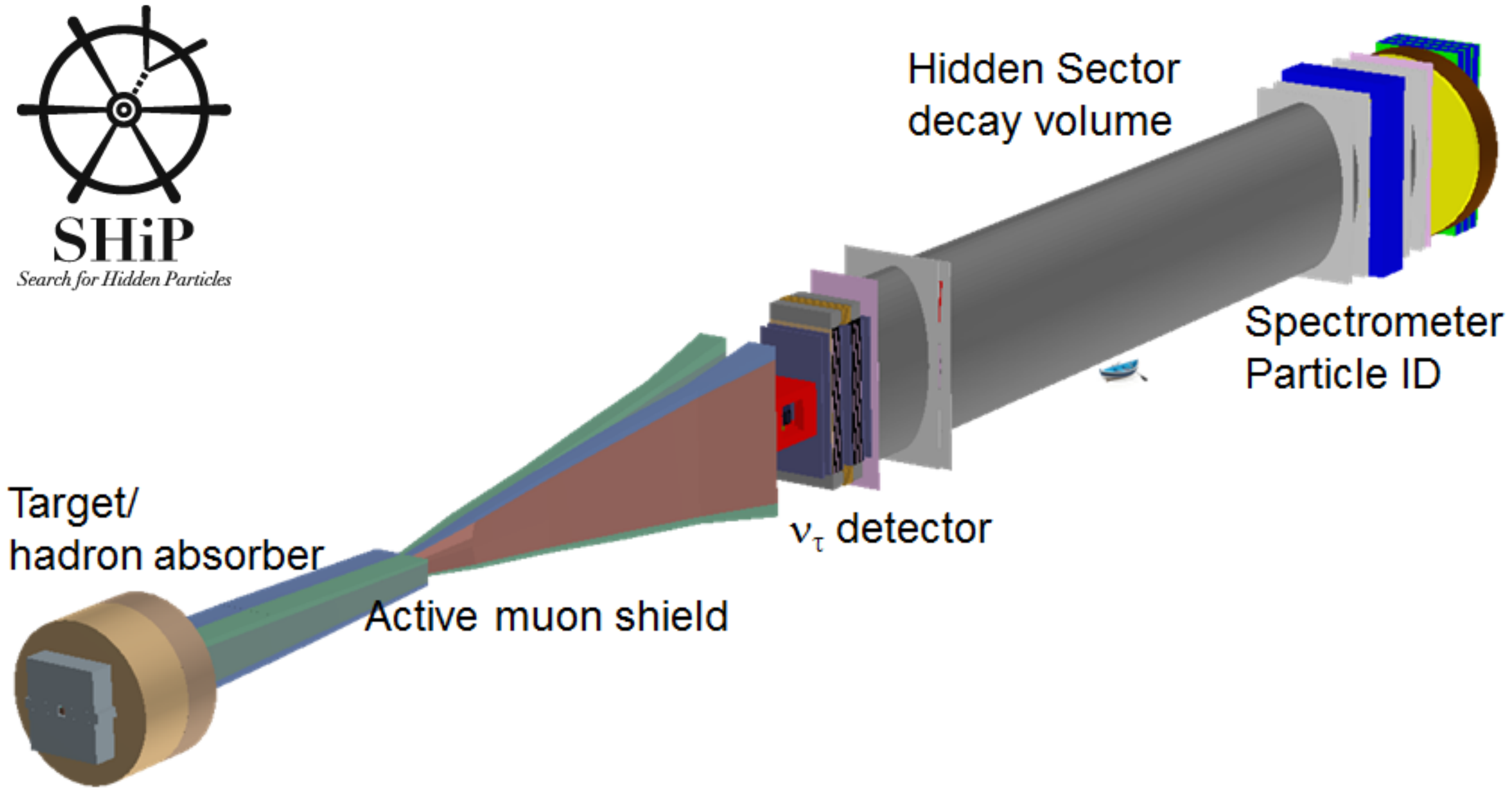
A kingdom for a magnet

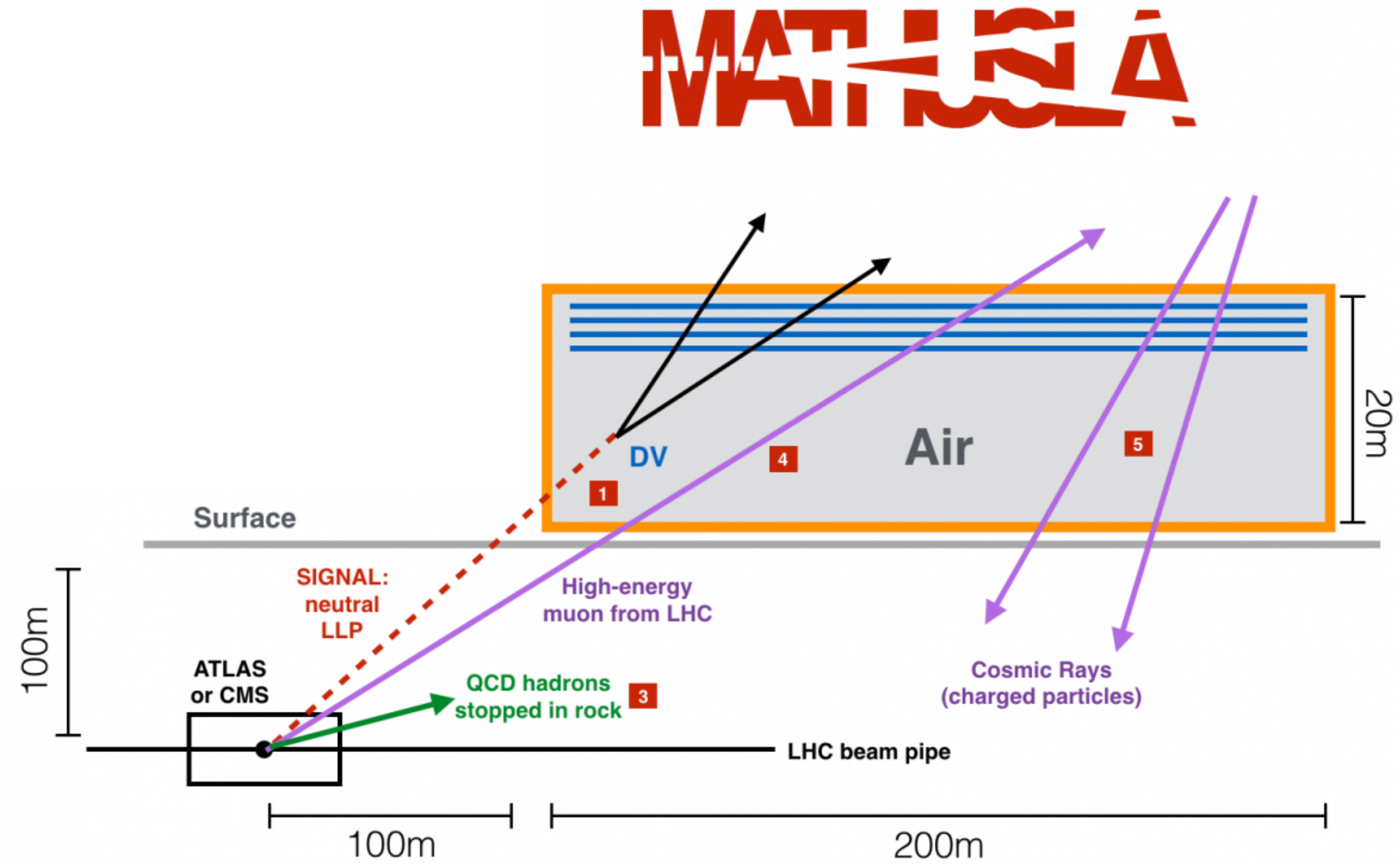
Fixed target : easy!



In fixed target mode on the other hand, even if your distance to the first measured point is large, all decay products go in a small geometrical cone, so quite possible to add a magnet

The quest for zero background





Considerations : size of shield, active layer for in-shield secondary production, vacuum decay vessel or calorimeter style detector (?), magnet or timing/calorimetry for reconstruction?

Fixed target case study : SHIP

Detector design

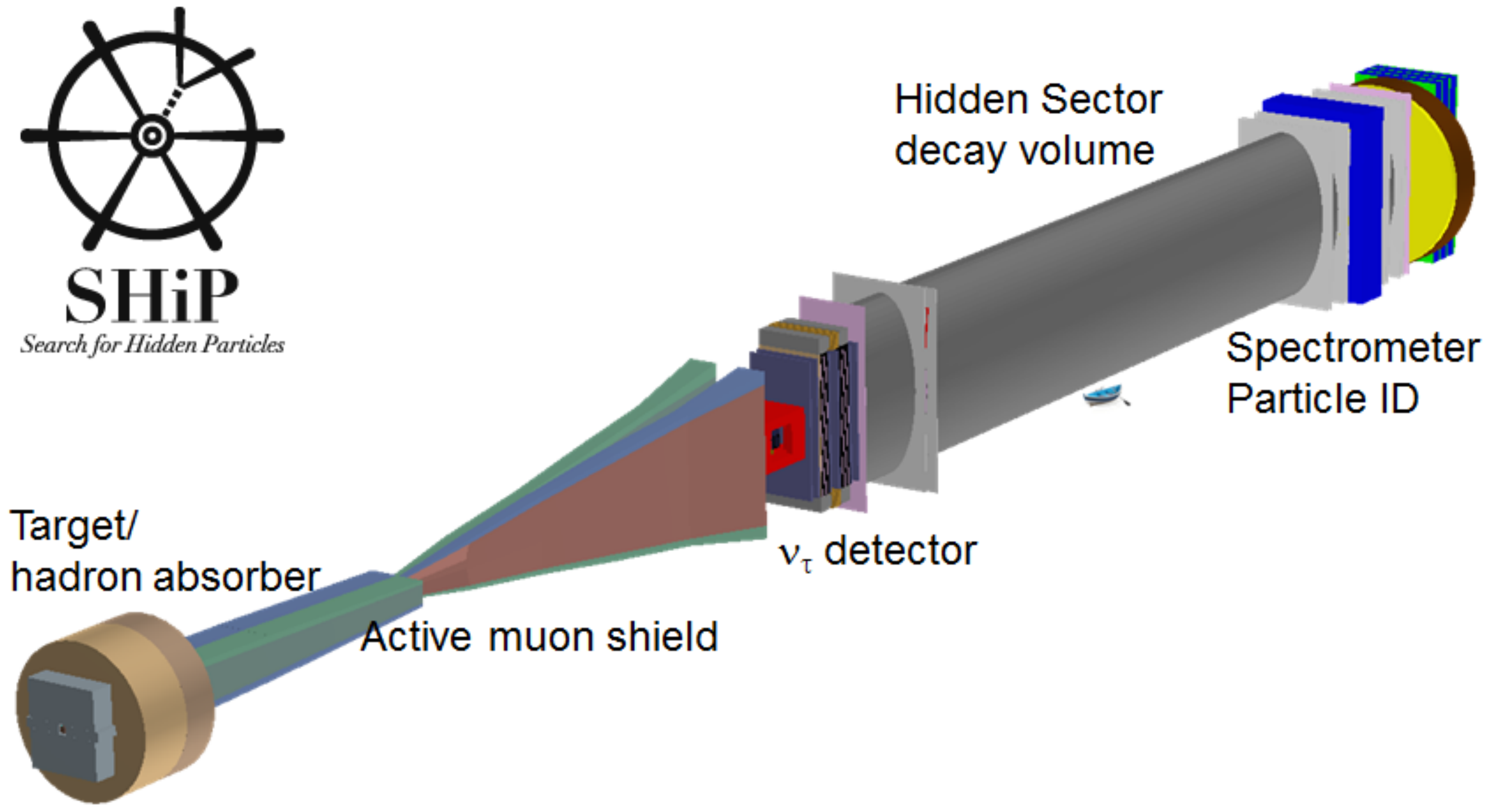
Key points :

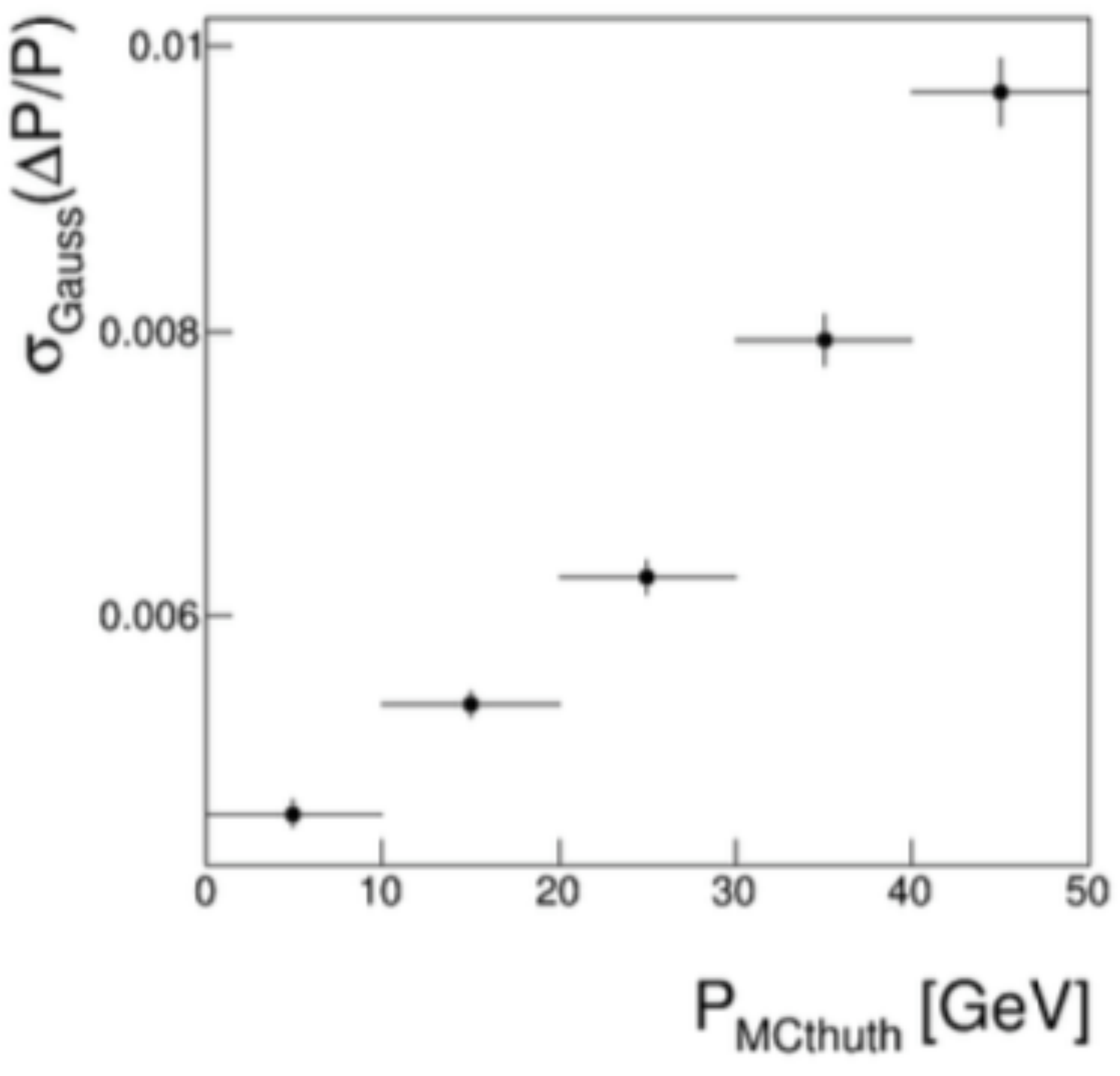
Active shield and vacuum decay volume to minimize backgrounds

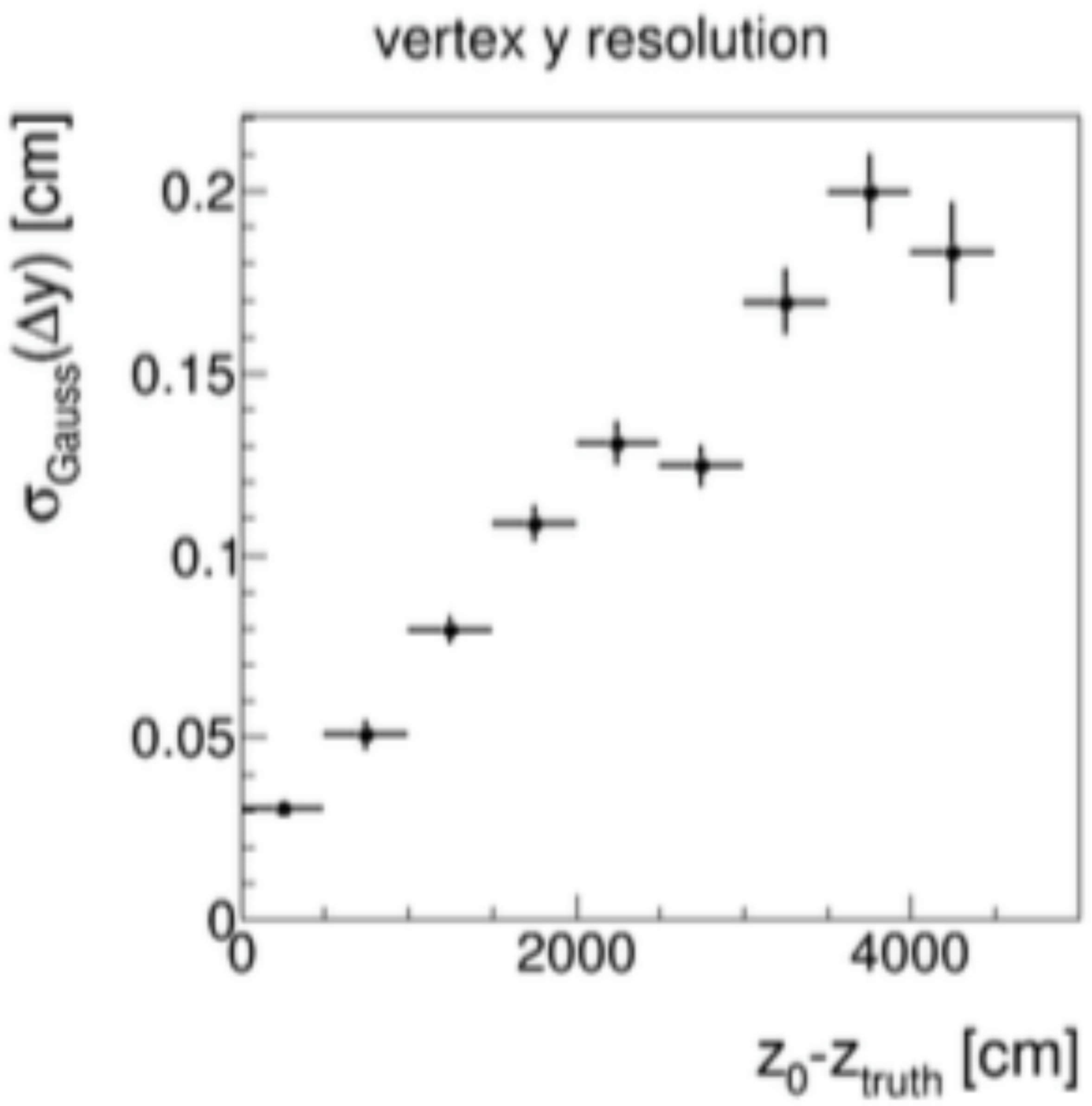
Sub percent momentum resolution, particle ID, mm vertex resolution in the transverse plane

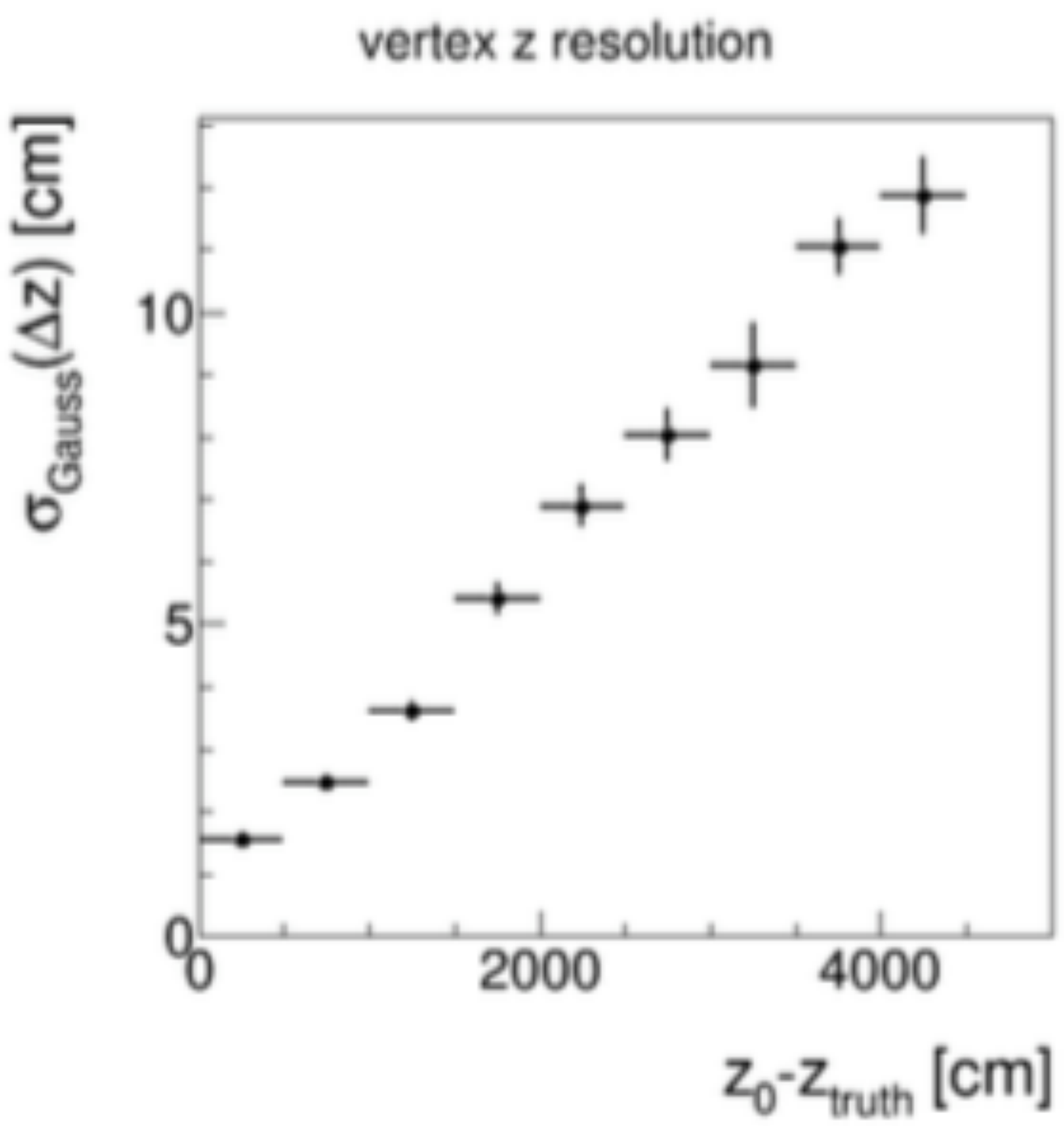
Timing coincidence (a la NA62) used to suppress backgrounds

Exploits boost of produced heavy flavour to improve acceptance for LLPs, particularly shorter lived ones

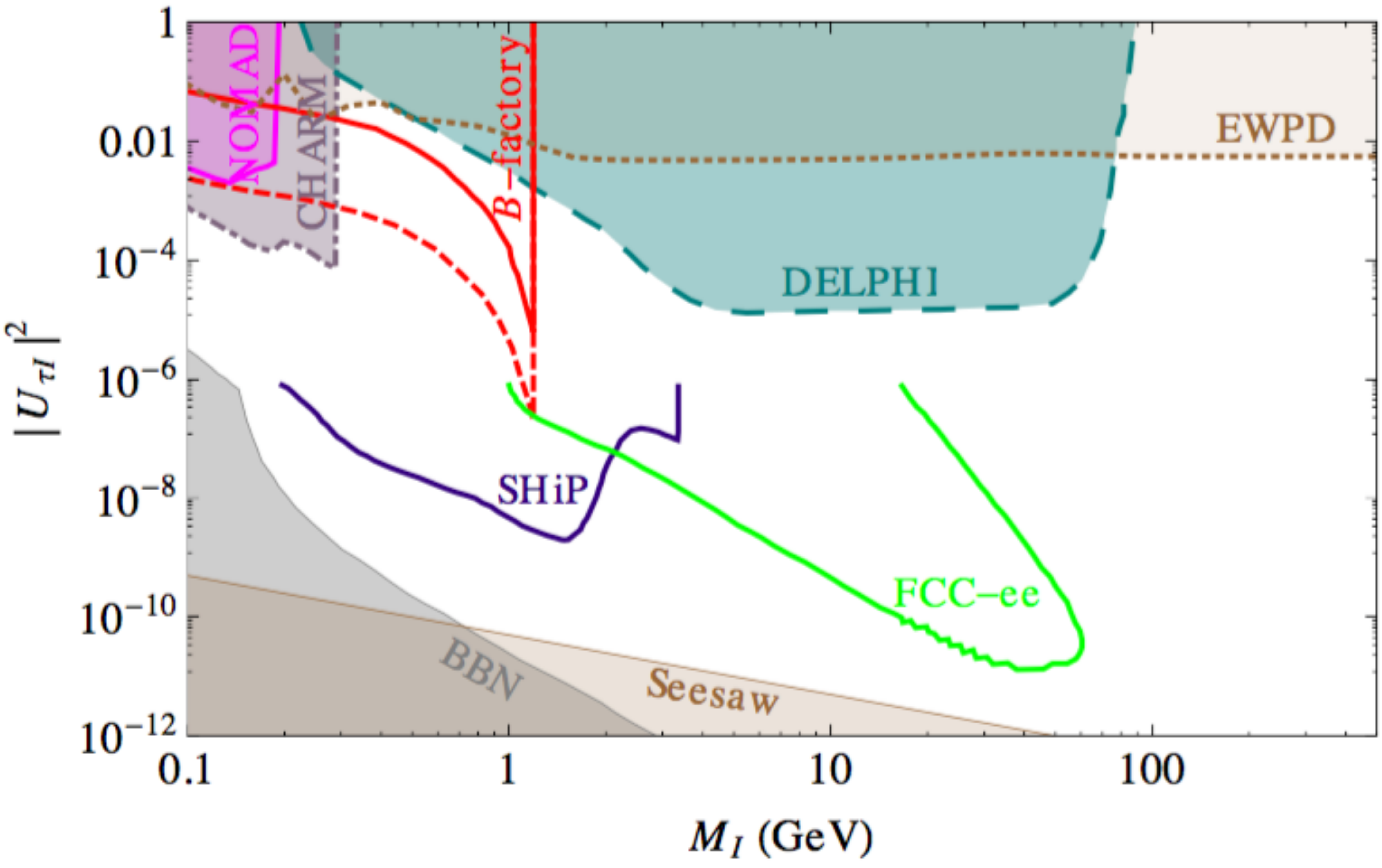




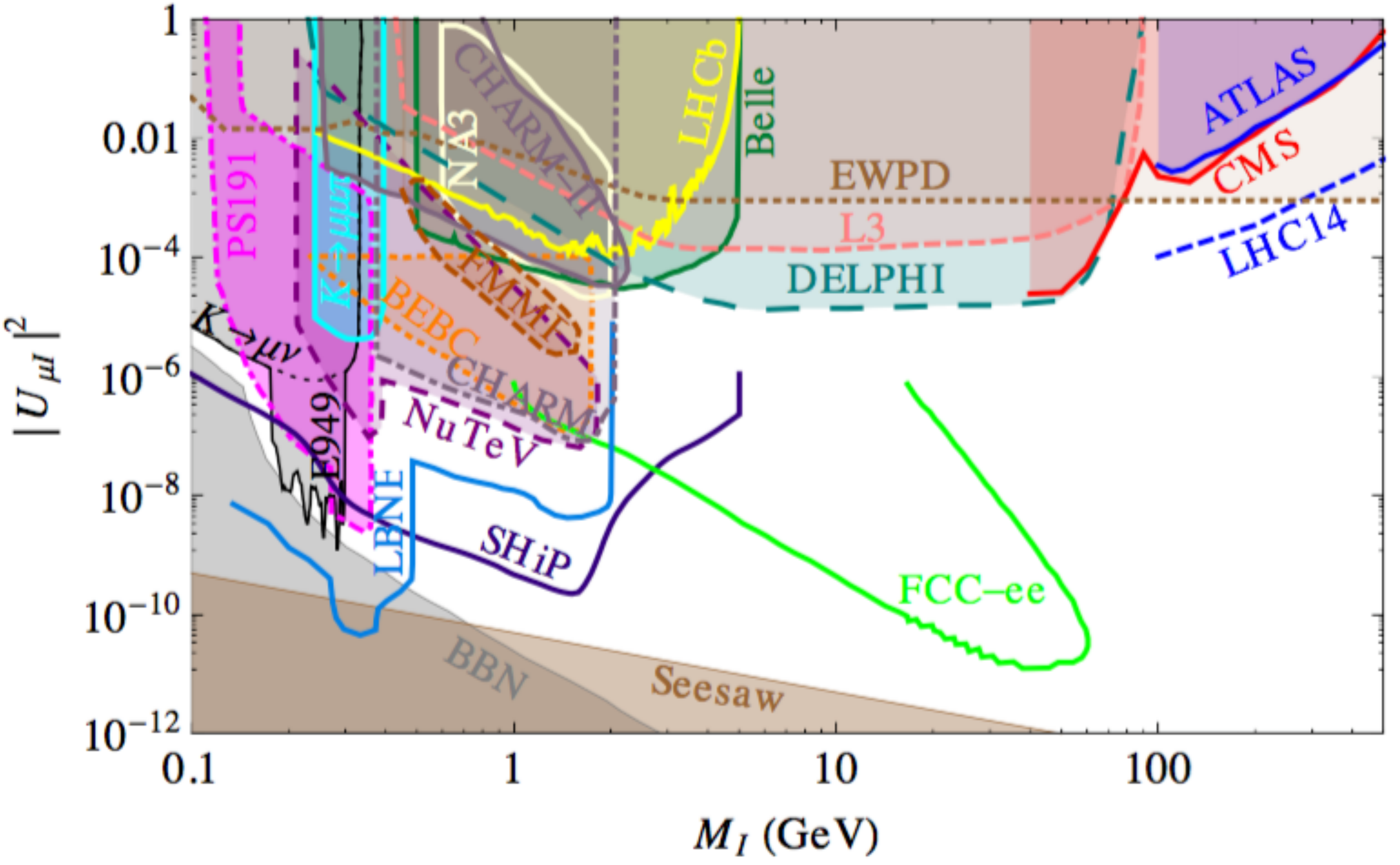




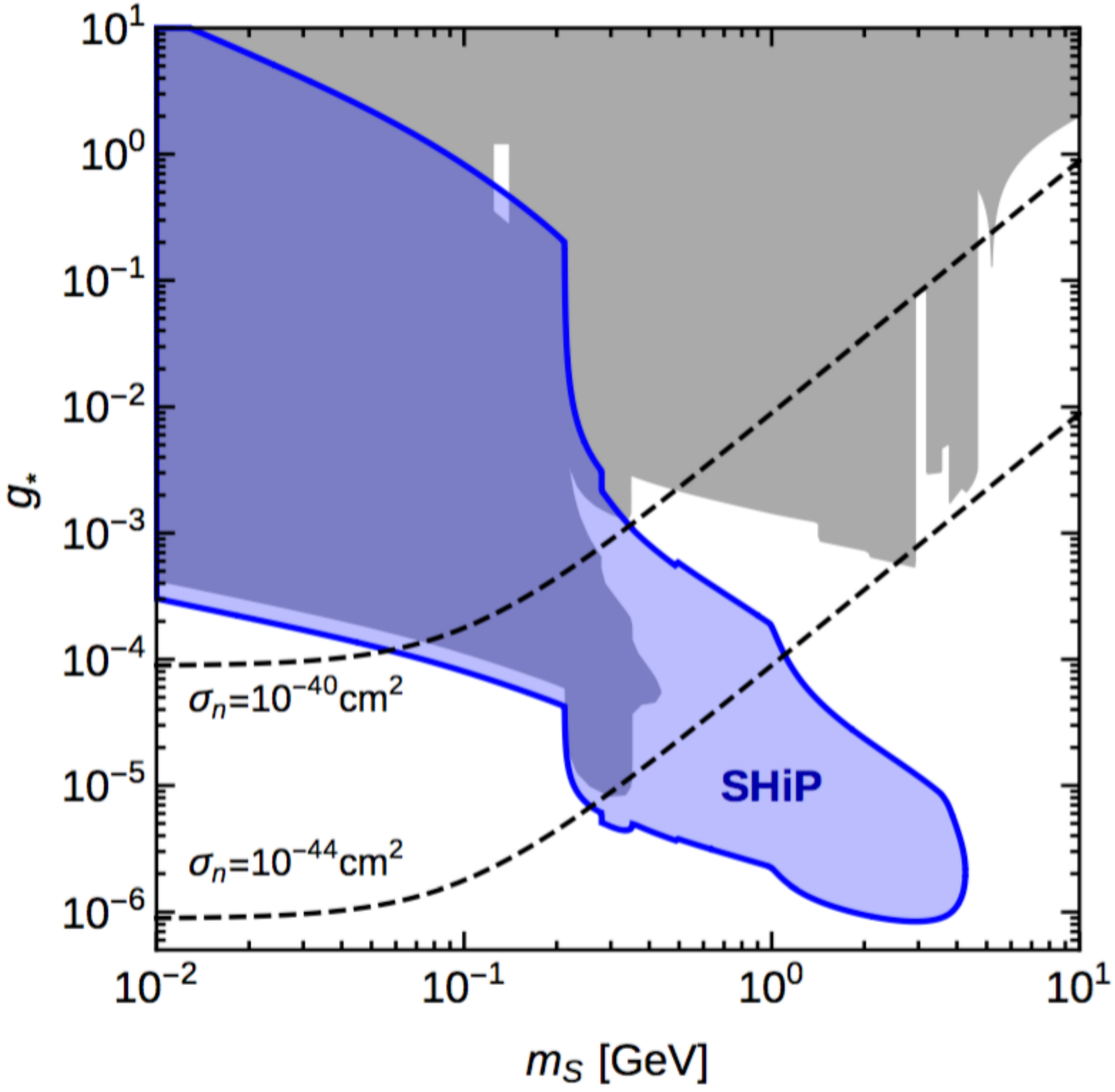
Reach estimates for HNLs



Reach estimates for HNLs



Reach estimates for b→sX



Collider case study : MATHUSLA

Detector design

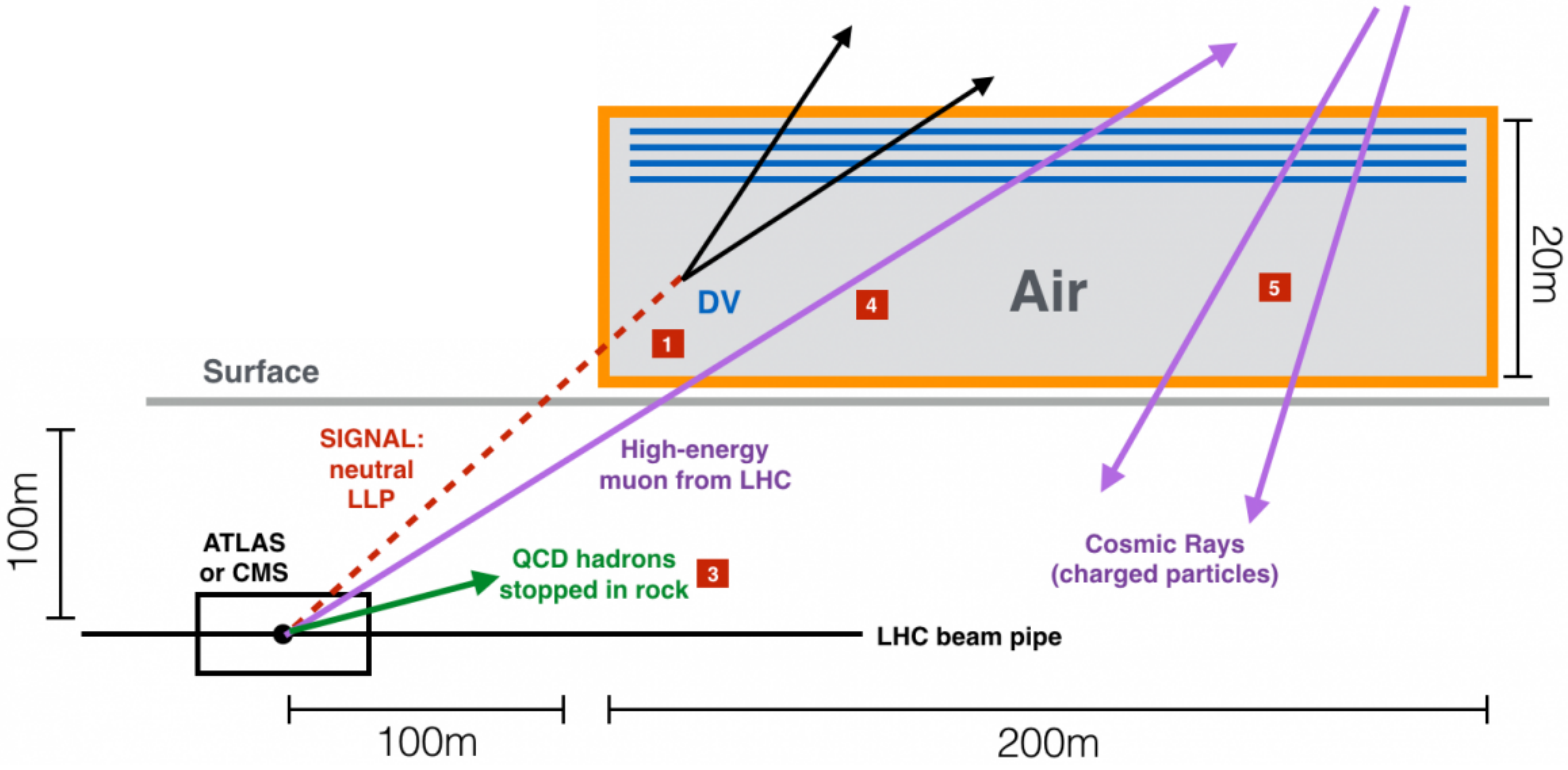
MATHUSLA

Key points :

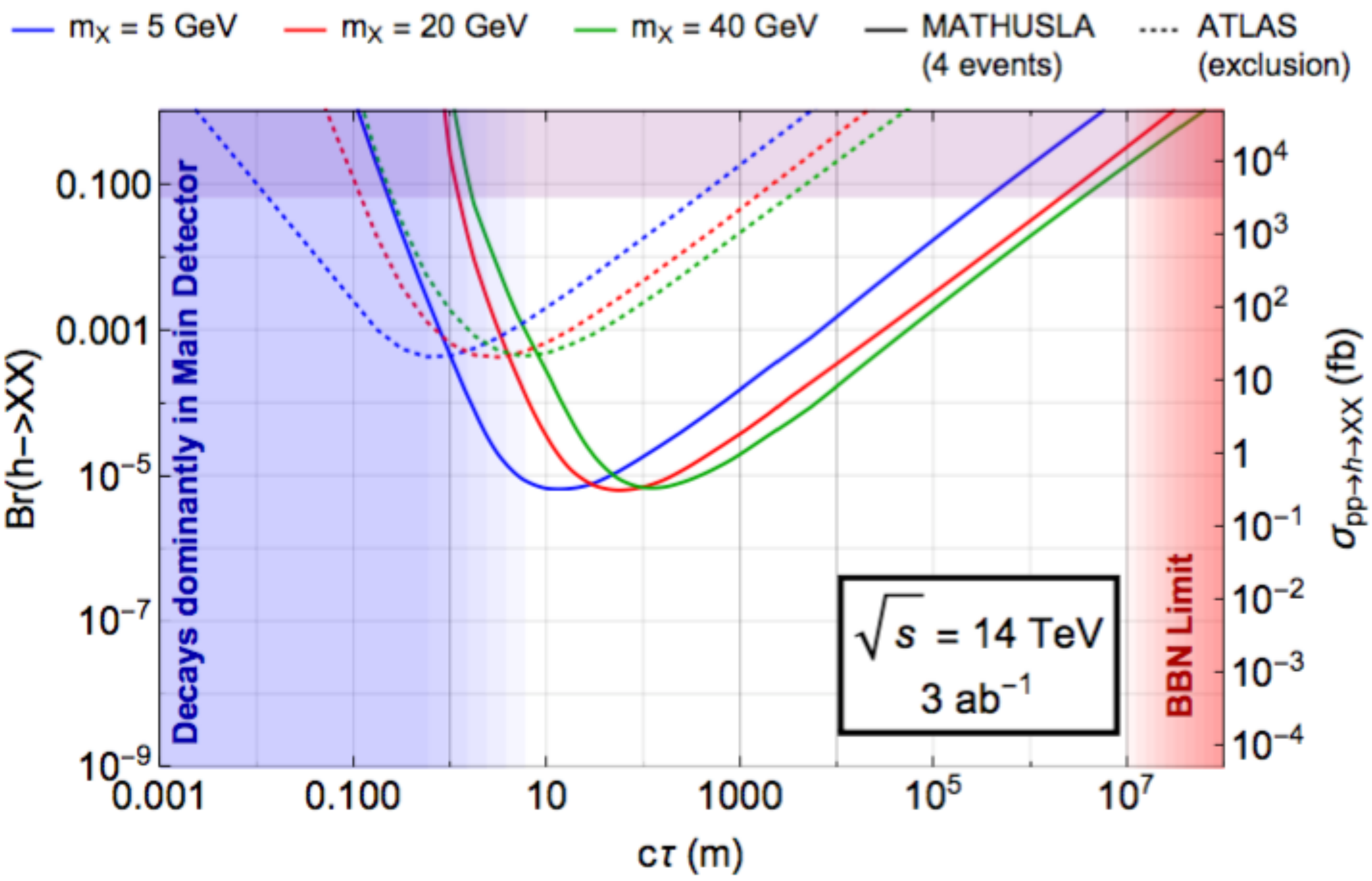
Access full HL-LHC luminosity

“Natural” shielding from LHC backgrounds, active vetoes on sides for cosmics and similar

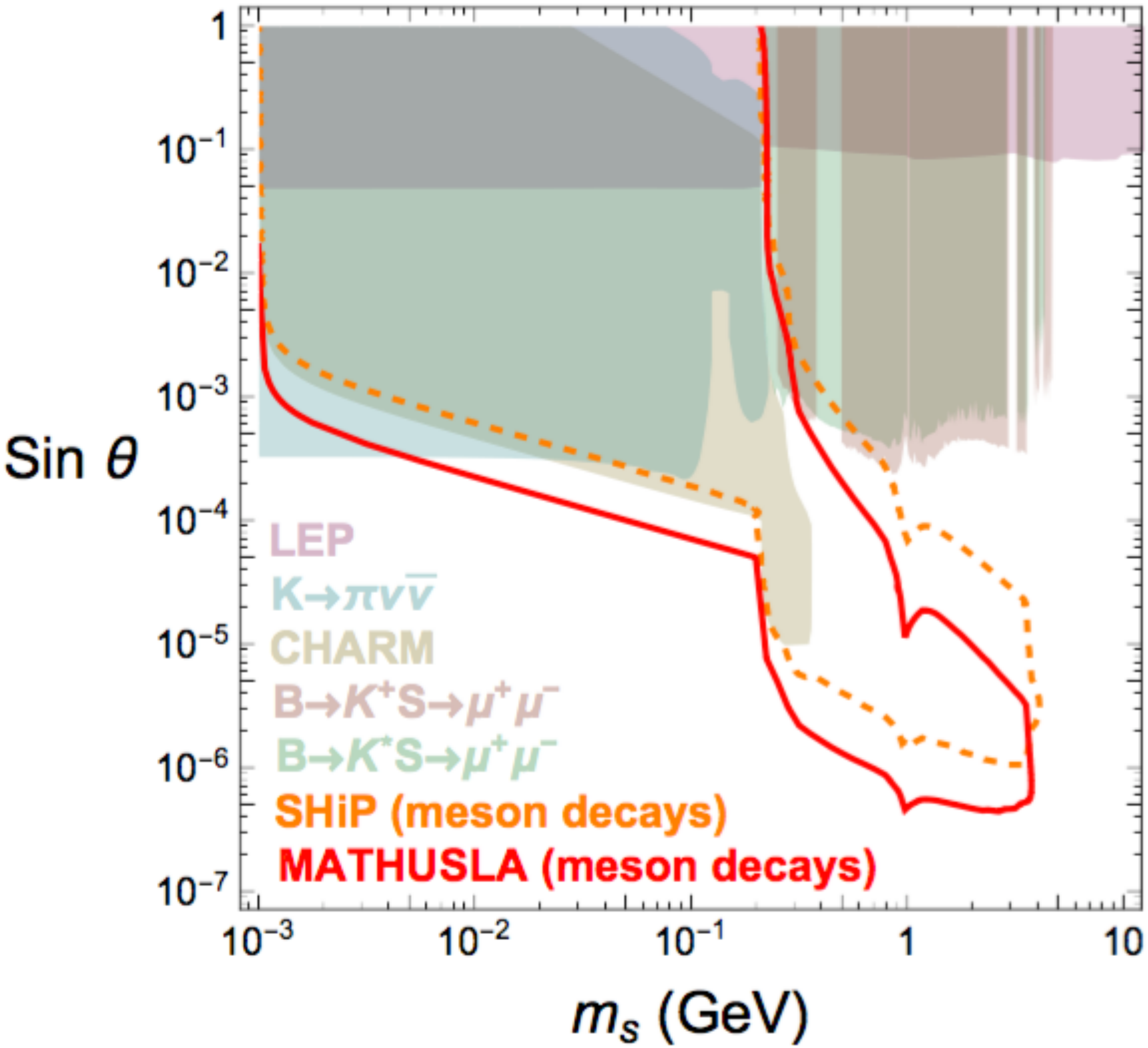
Enormous size : several tracking layers of 200x200 m^2 each



Reach estimates for Higgs portal

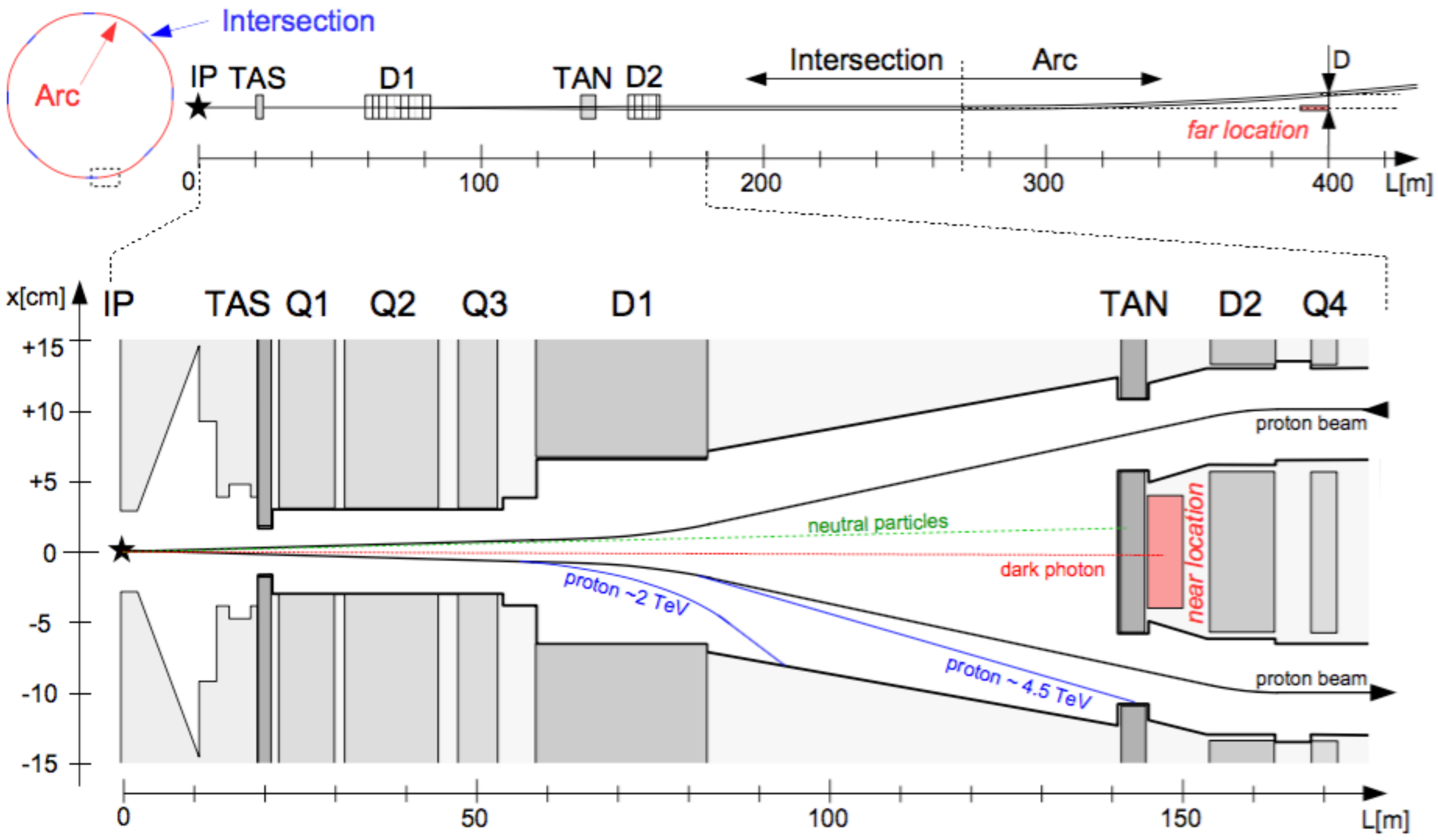


Reach estimates for b→sX



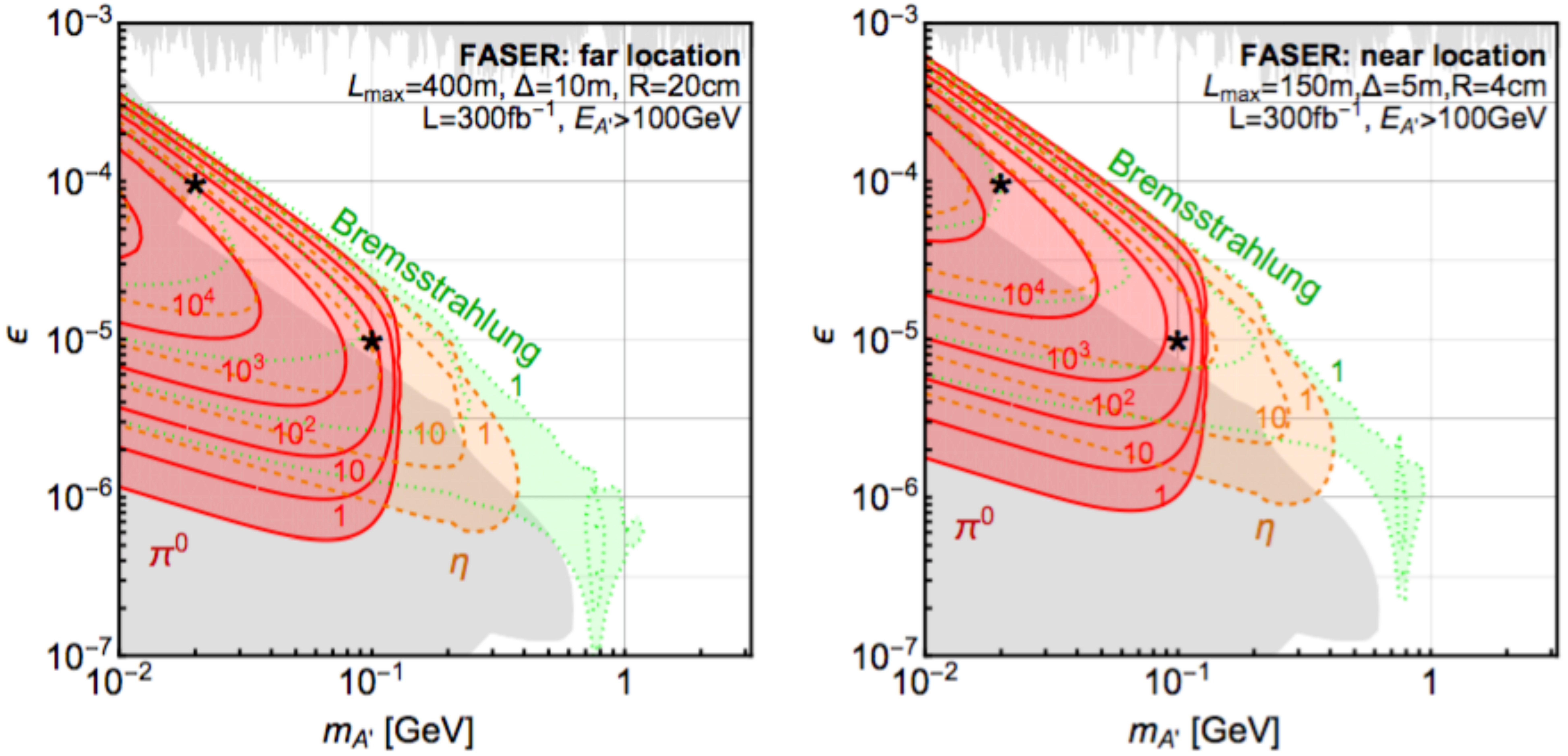
Collider case study : FASER

Detector design



Very forward, exploits tail of the boost distribution

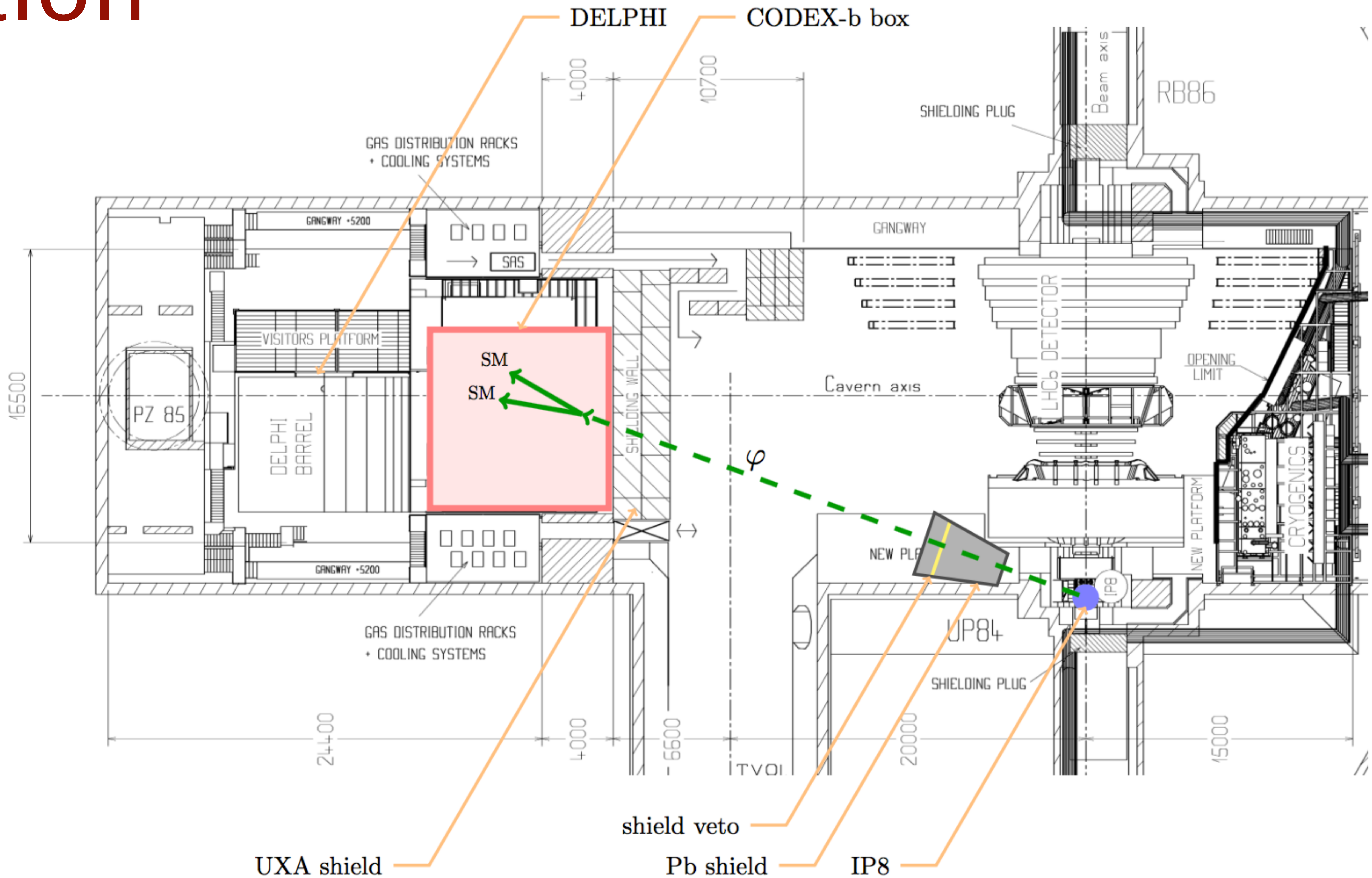
Reach estimates for dark photons



Production of proton brems (!) highlights unique forward regime

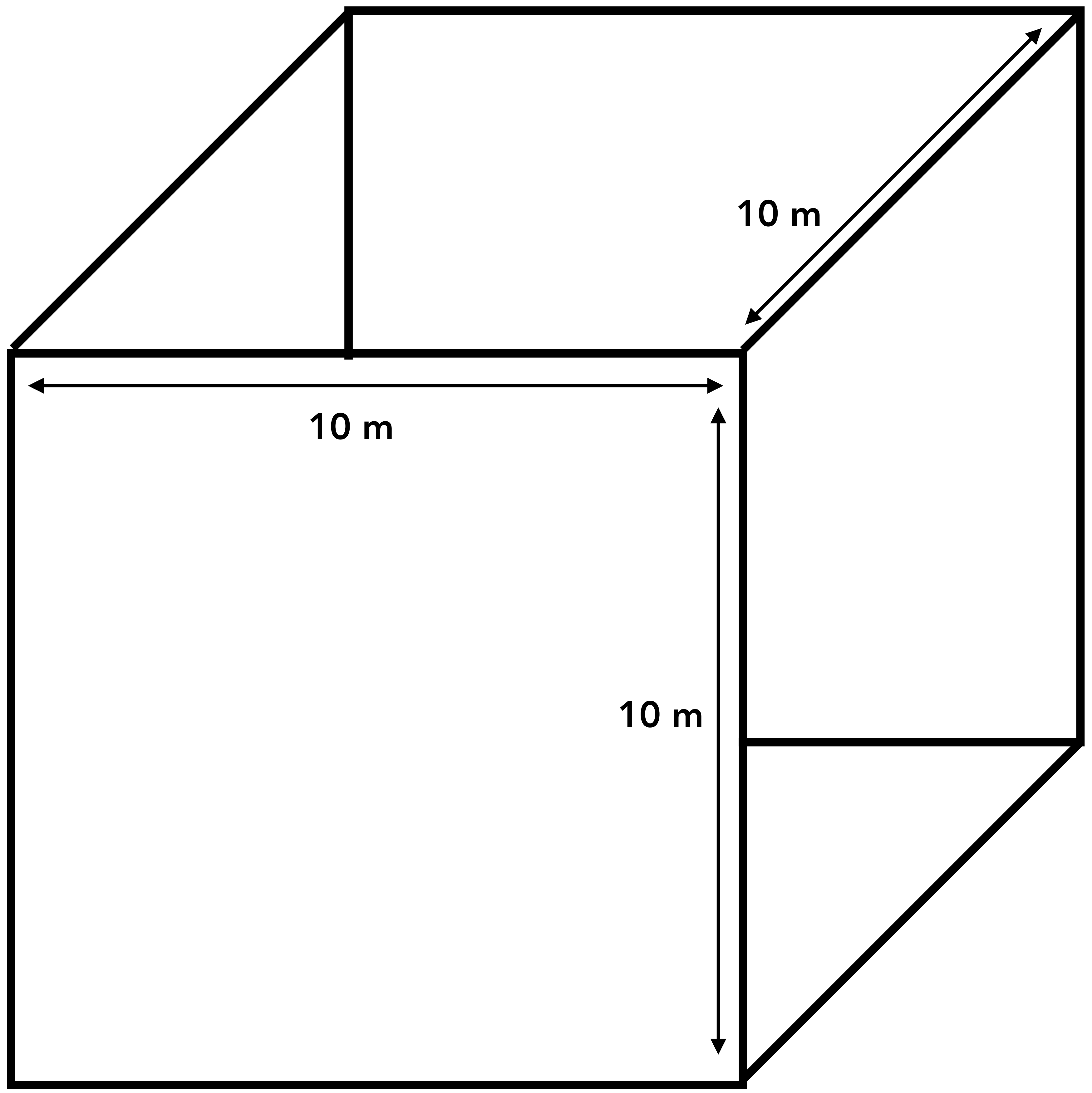
Collider case study : CODEX-b

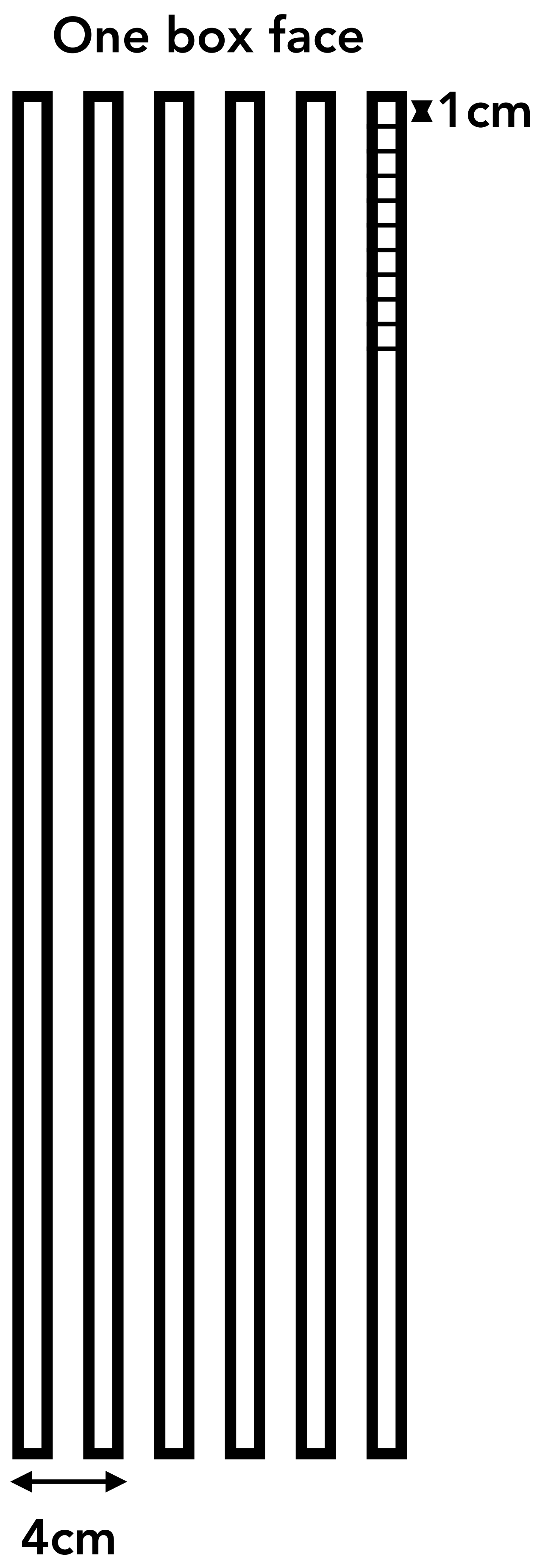
Location



DELPHI
CODEX-b box
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
GANGWAY +5200
SAS
VISITORS PLATFORM
PZ 85
DELPHI BARREL
SM
SM
SHIELDING WALL
φ
Cavern axis
GANGWAY
SHIELDING PLUG
Beam axis
RB86
LHCb DETECTOR
OPENING LIMIT
NEW PLATFORM
CRYOGENICS
IP8
UP84
NEW PL
4000
10700
16500
24400
6600
20000
15000
TV01
UXA shield
shield veto
Pb shield
IP8

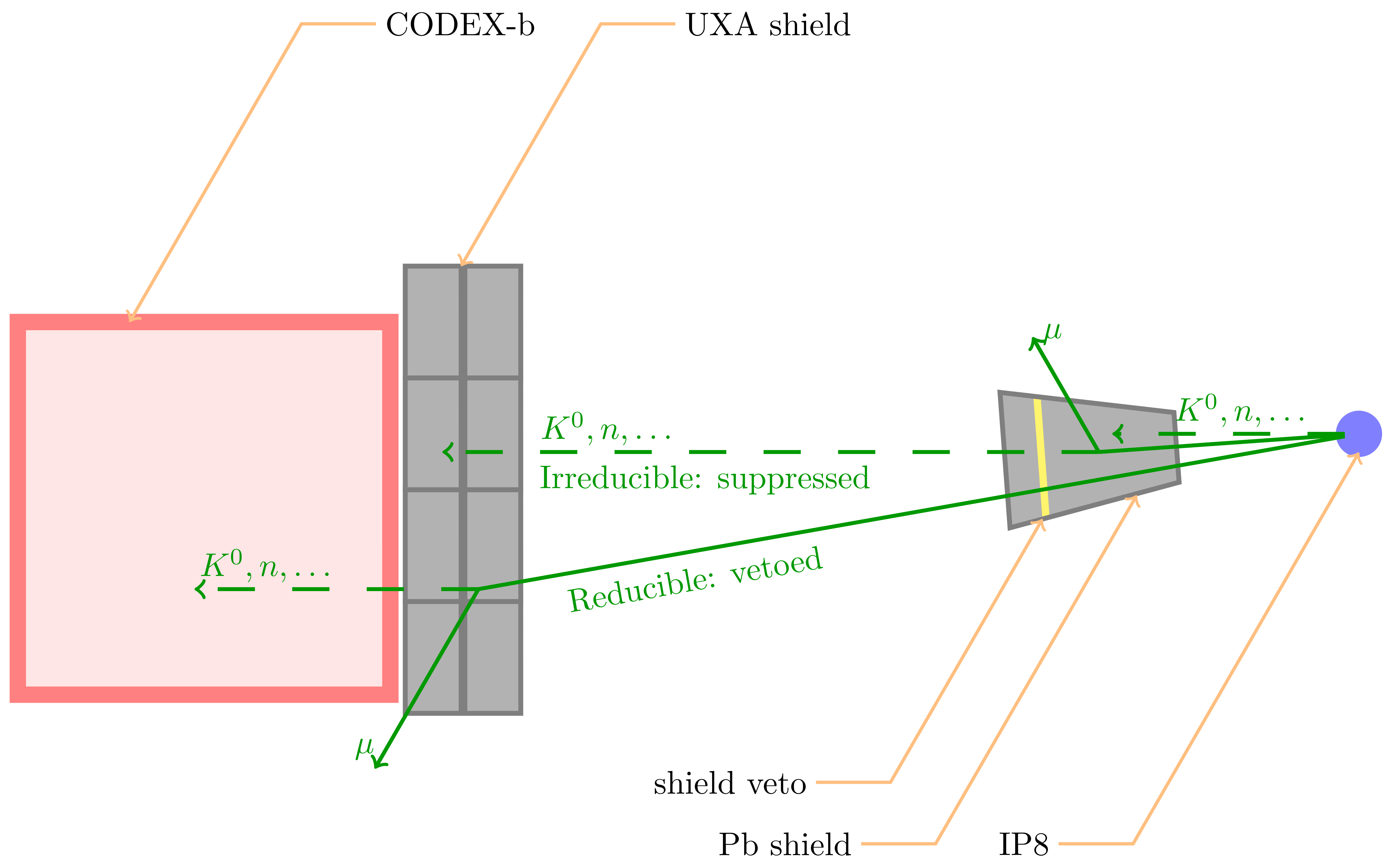
Minimal proof-of-concept geometry





10x10x10 metre box, with 6 RPC layers on each box face. Assume 1 cm granularity for the RPCs, and possibility of timing information (explored later in talk). Add 5 other triplets of RPC layers equally spaced in box to minimize the distance to the first measured point for the decay vertex determination.

Minimal shield & veto design



Simple design : use first part of the shield to attenuate muon & neutral hadron backgrounds which could enter the detector volume and scatter or decay within it, faking a signal. Then use a thin veto layer to eliminate secondary production of backgrounds within the shield itself.

Basic GEANT background estimate

BG species	Particle yields		Baseline Cuts
	irreducible by shield veto	reducible by shield veto	
$n+\bar{n}$	7	$5\cdot 10^4$	$E_{\text{kin}} > 1\,\text{GeV}$
K_L^0	0.2	870	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\pi^\pm + K^\pm$	0.5	$3\cdot 10^4$	$E_{\text{kin}} > 0.5\,\text{GeV}$
$\nu+\bar{\nu}$	0.5	$2\cdot 10^6$	$E > 0.5\,\text{GeV}$

Simulate initial background flux with Pythia 8, propagate through shield, air, and detector using GEANT4. A few things to note :

— Nominally largest background is neutrons entering the box
— Muon-air interactions can be vetoed using front detector faces
— Neutrino backgrounds are entirely negligible.

No attempt yet to use any properties of reconstructed backgrounds to reject them, but timing + spatial information should help there.

Energy spectrum of backgrounds

BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n + \bar{n}$	7	$5 \cdot 10^4$	$E_{\rm kin} > 1\,\text{GeV}$
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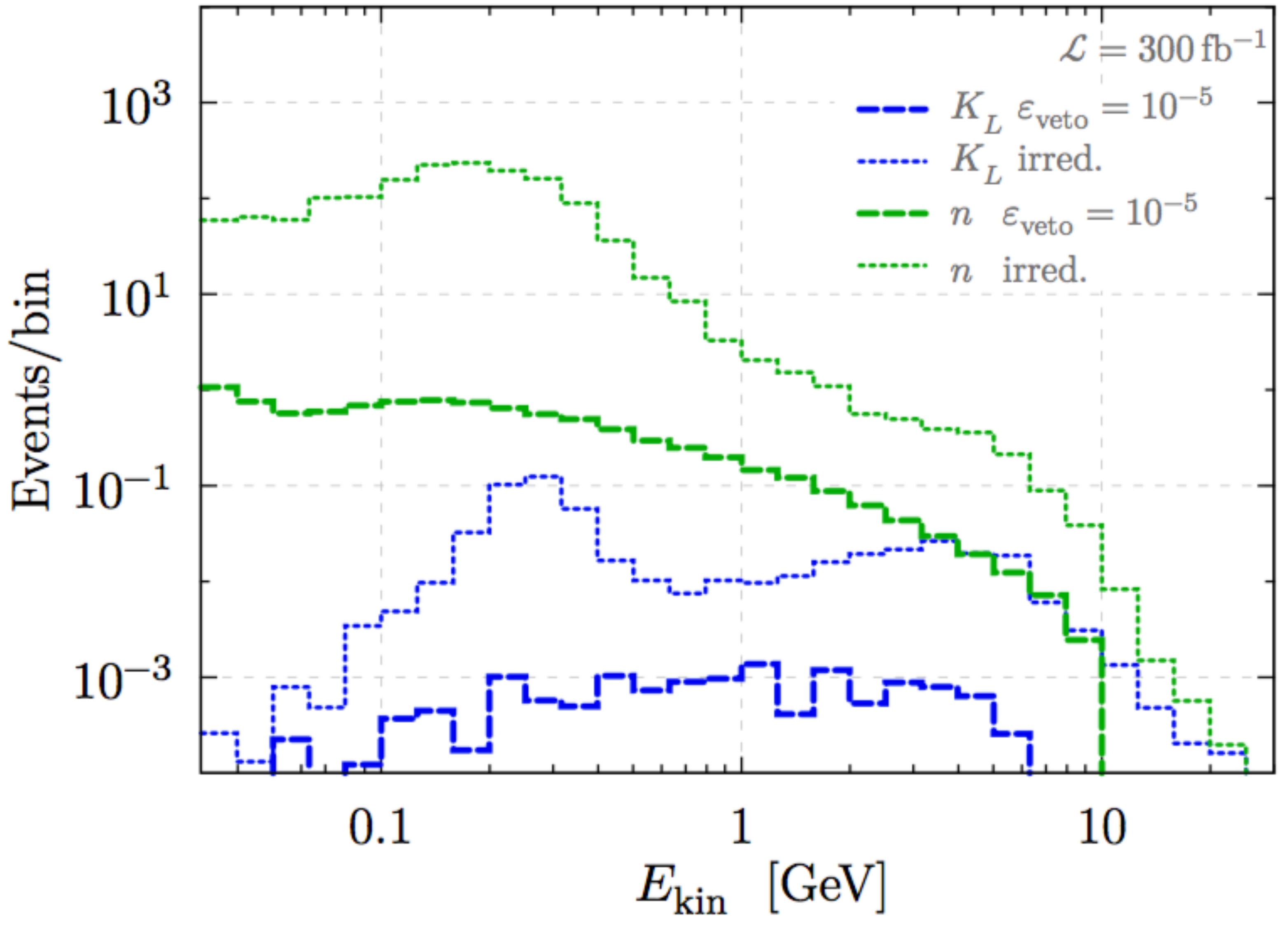
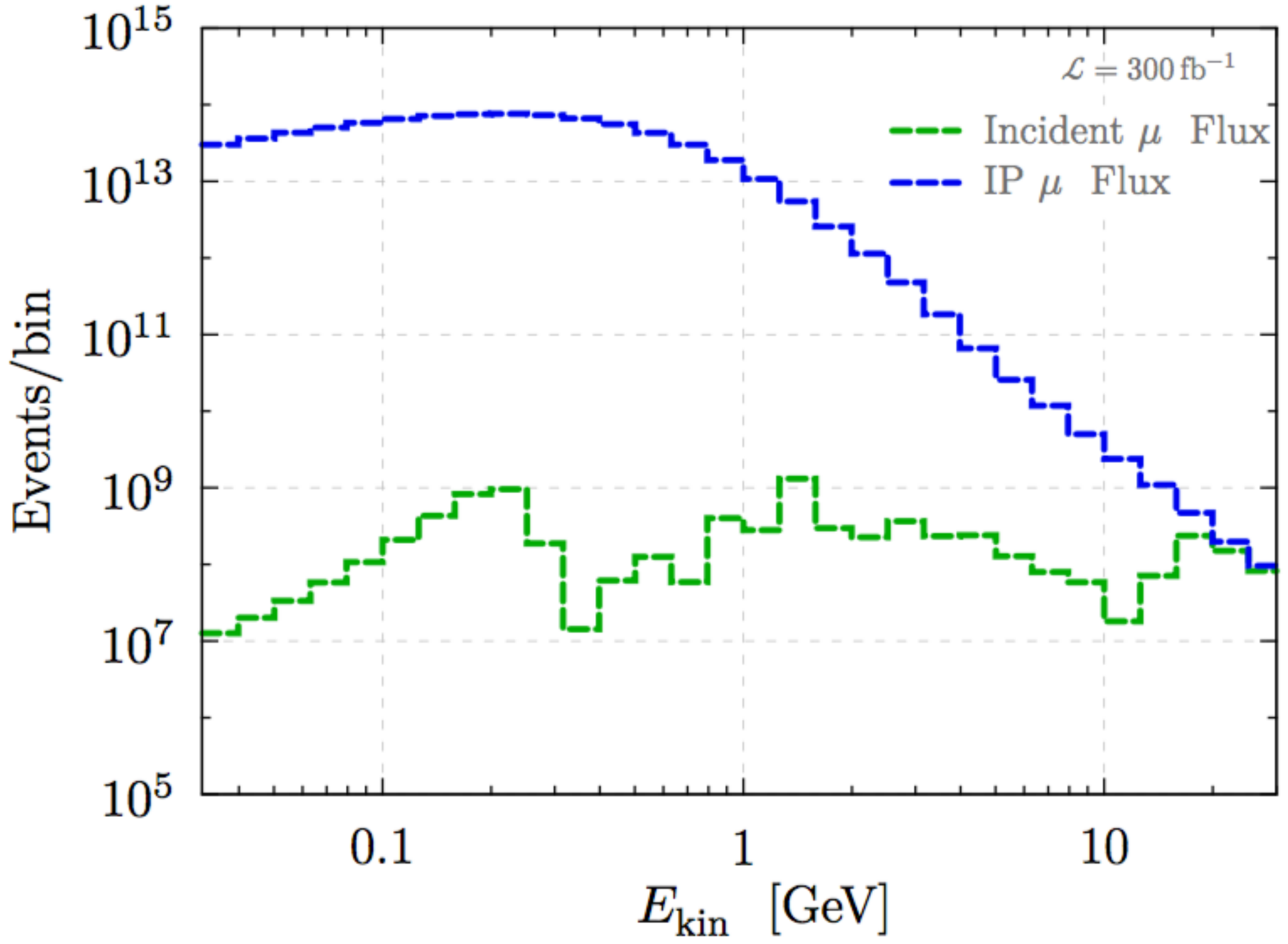


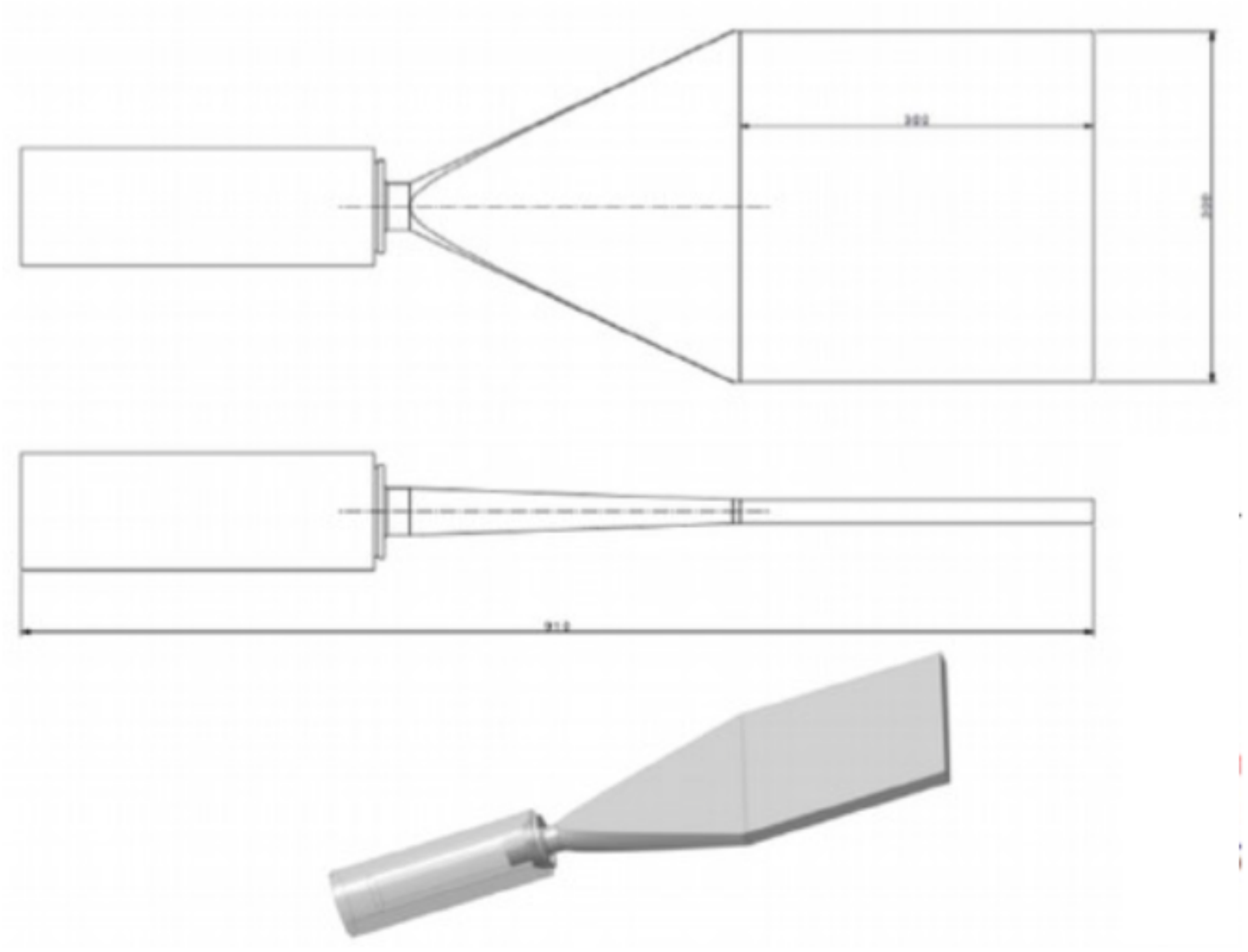
These are the numbers of unvetoable particles entering the box, the estimated number of scatters in box is <1 for all particle species!

Also notice the energy spectrum of these particles : most of them, especially the neutrons, are very soft!



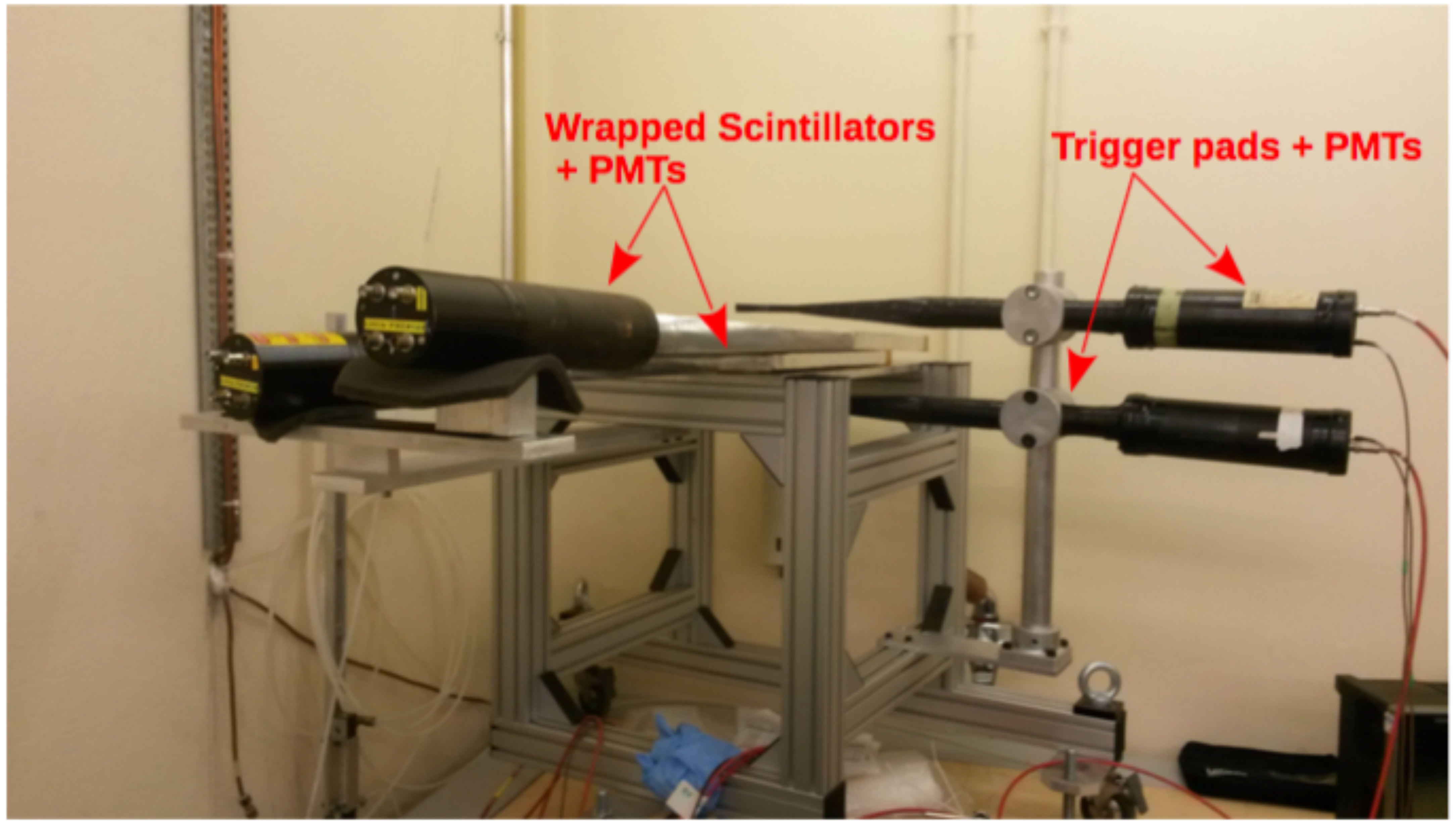
Backgrounds from data

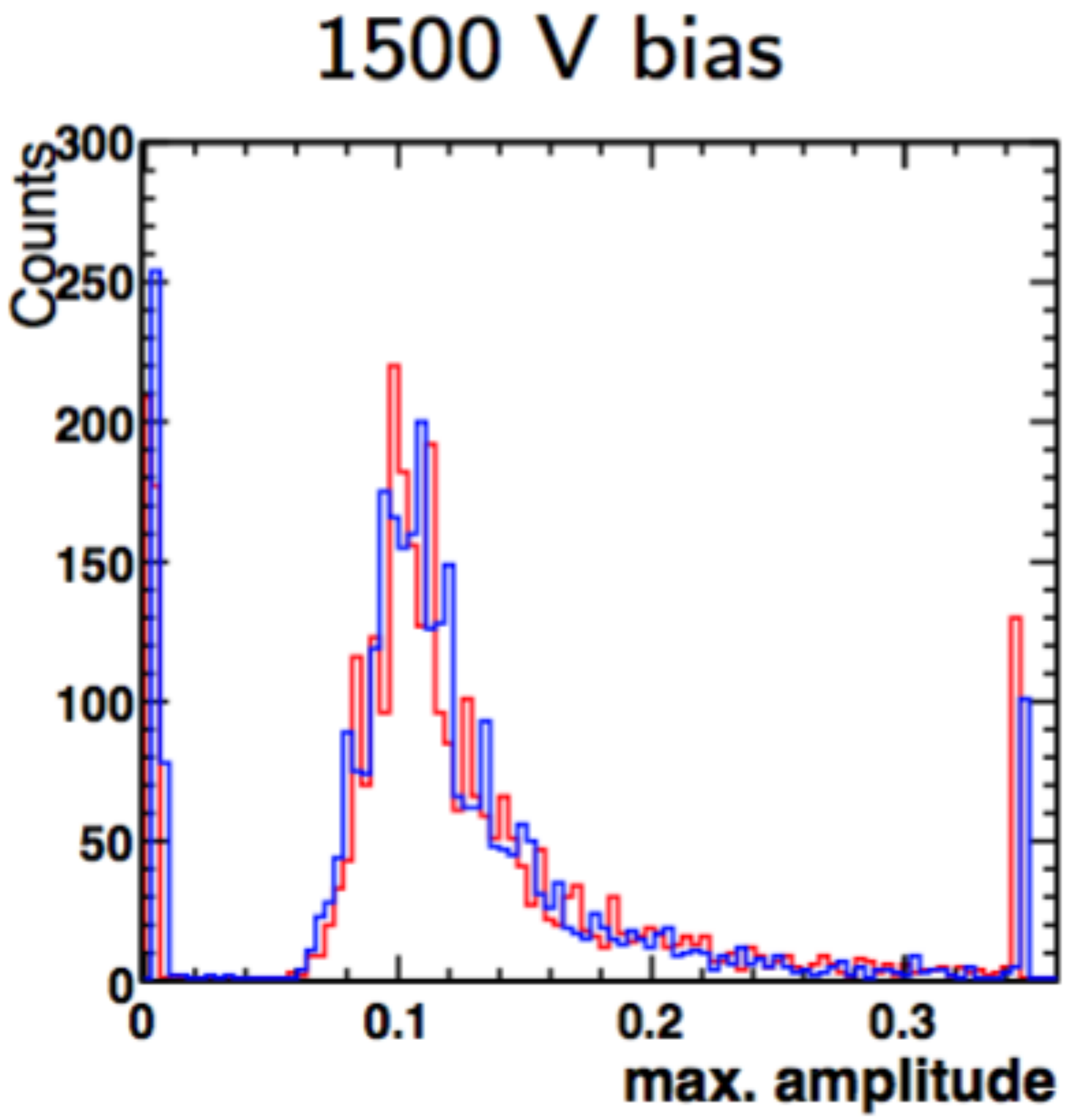
- Two 30 × 30 × 2 cm wrapped plastic scintillators + PMT + mechanical stand.



Backgrounds from data

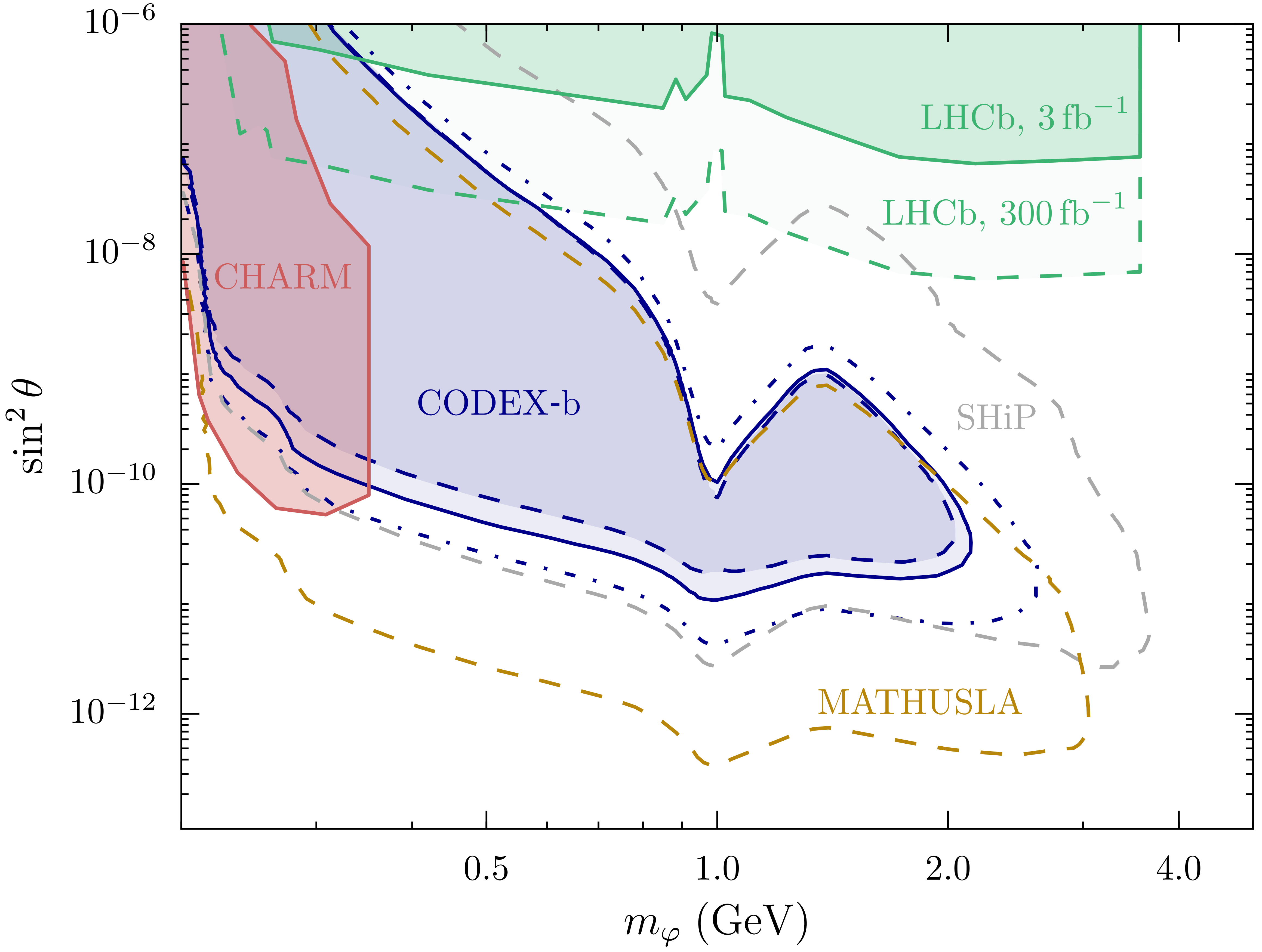
- Setup tested with cosmics. $\mathcal{O}(3000)$ in a couple of hours.

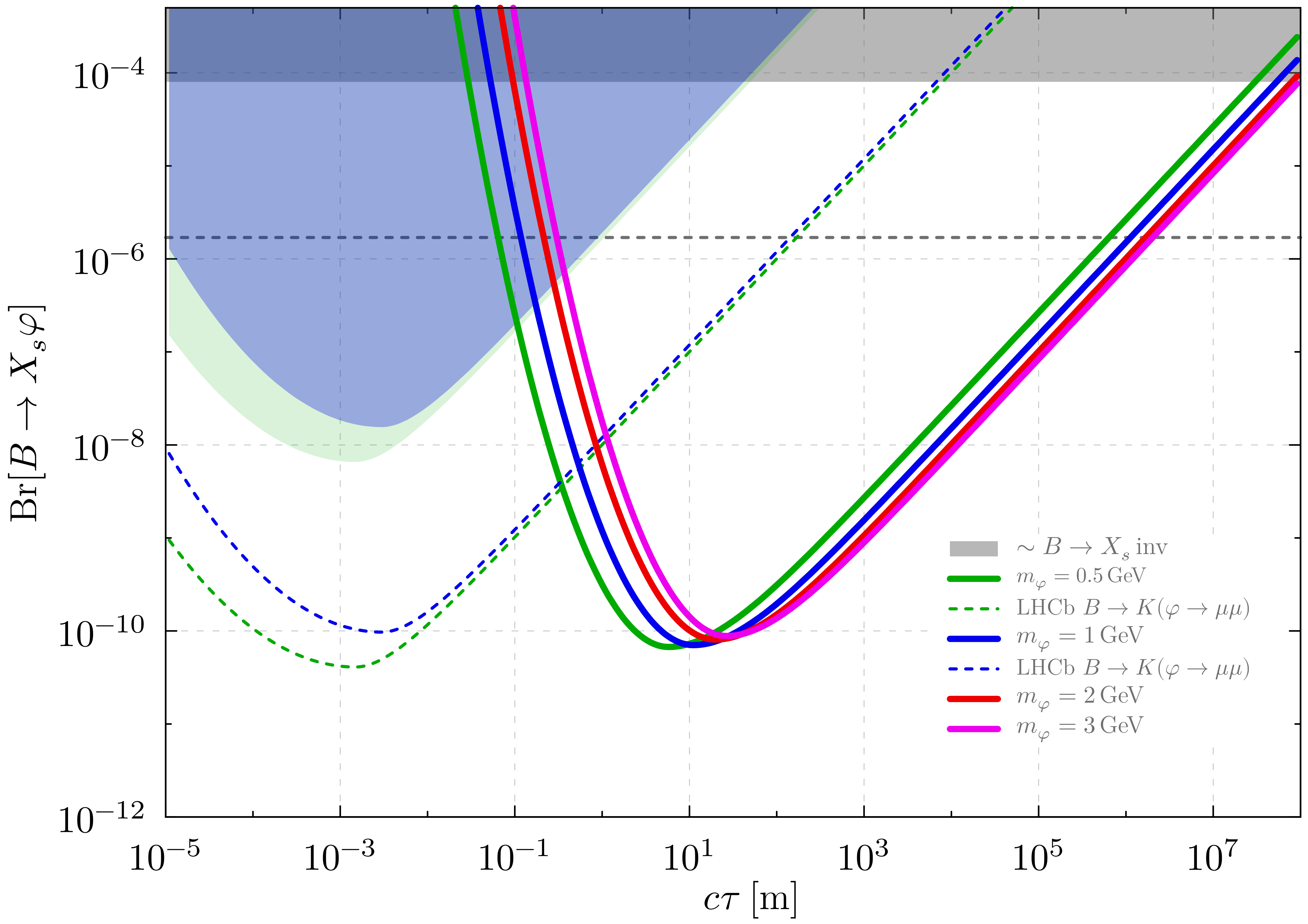




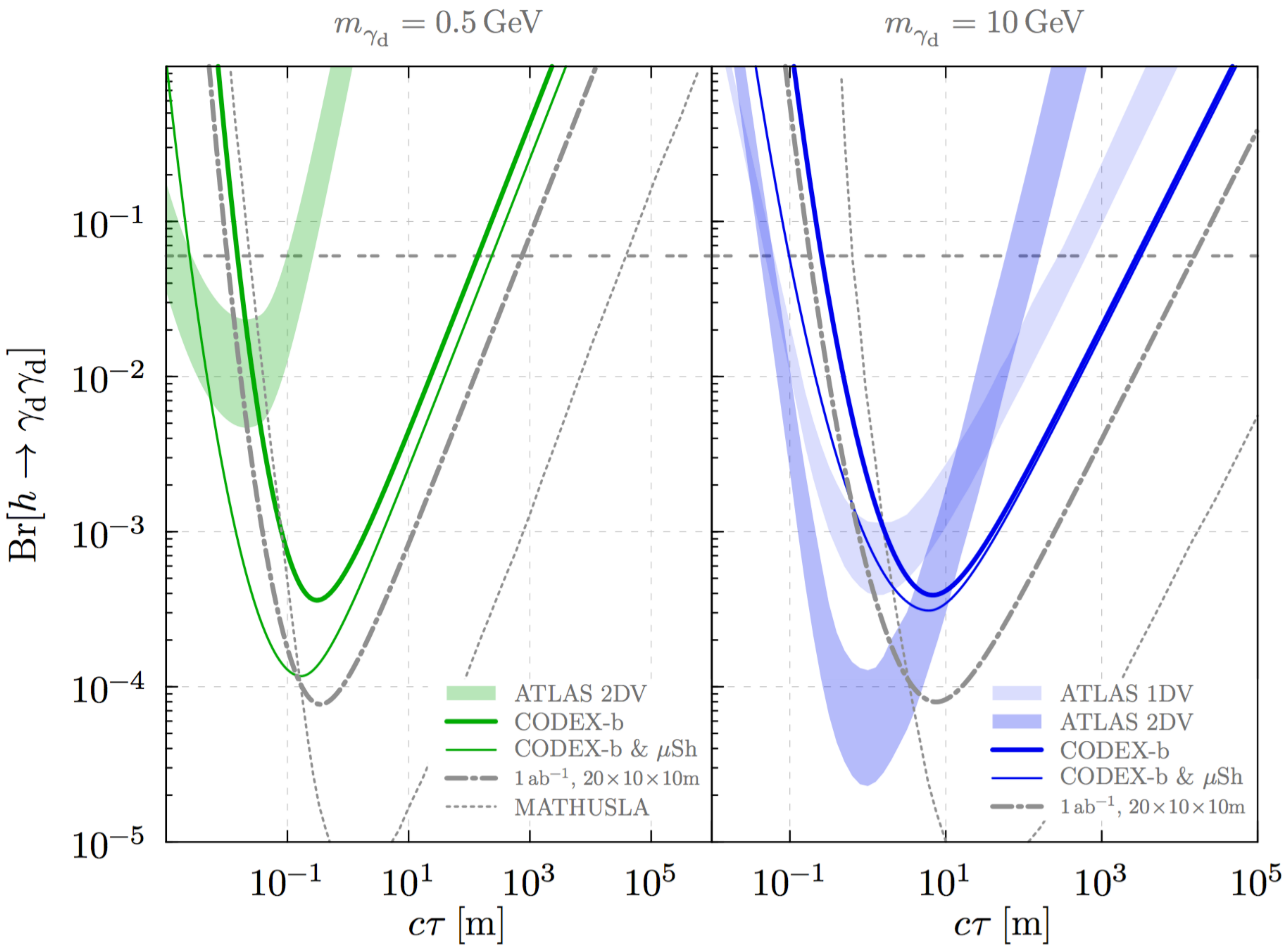
- Hope to get get enough events within around a week in the cavern.

Example model 1 — b→sX



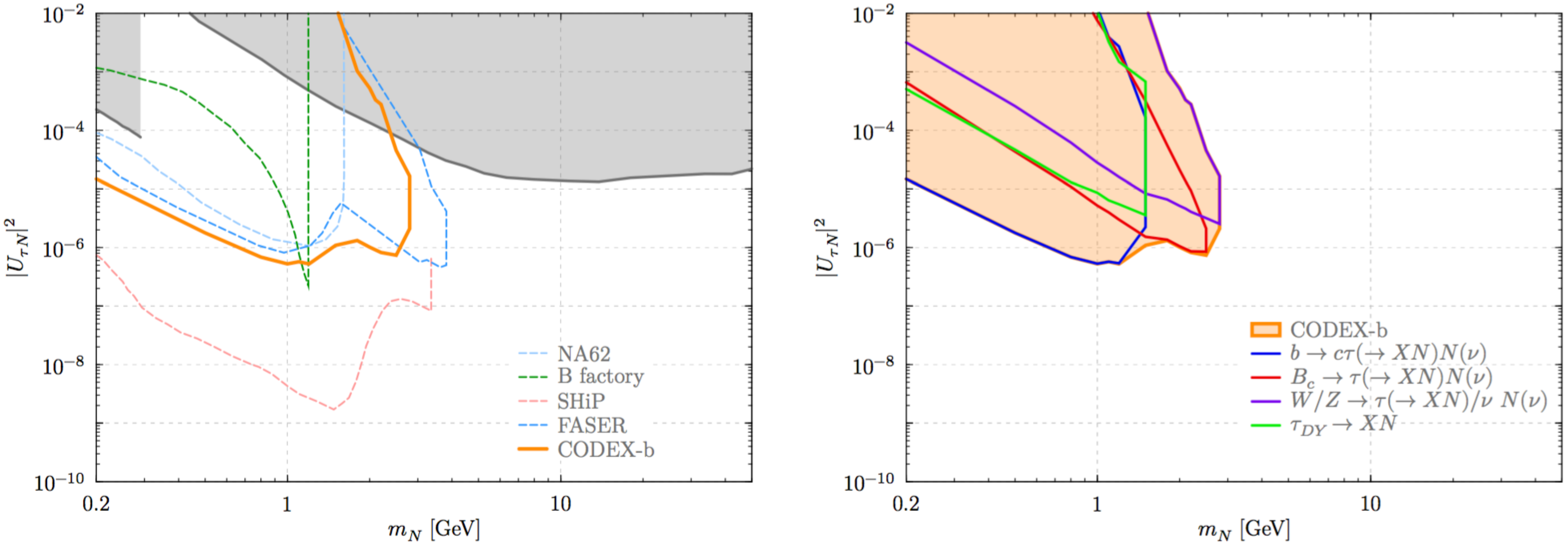


Example model 2 — H→φφ



Extends LHCb coverage far beyond ATLAS at low masses, competitive&complementary at higher ones. MATHUSLA has greater reach but backgrounds are uncorrelated.

Example model 3 — HNL



- Only weak limits set by current data!
- Reach dominated by B, B_c decays; W, Z in short lifetime regime

Tracker efficiency estimate

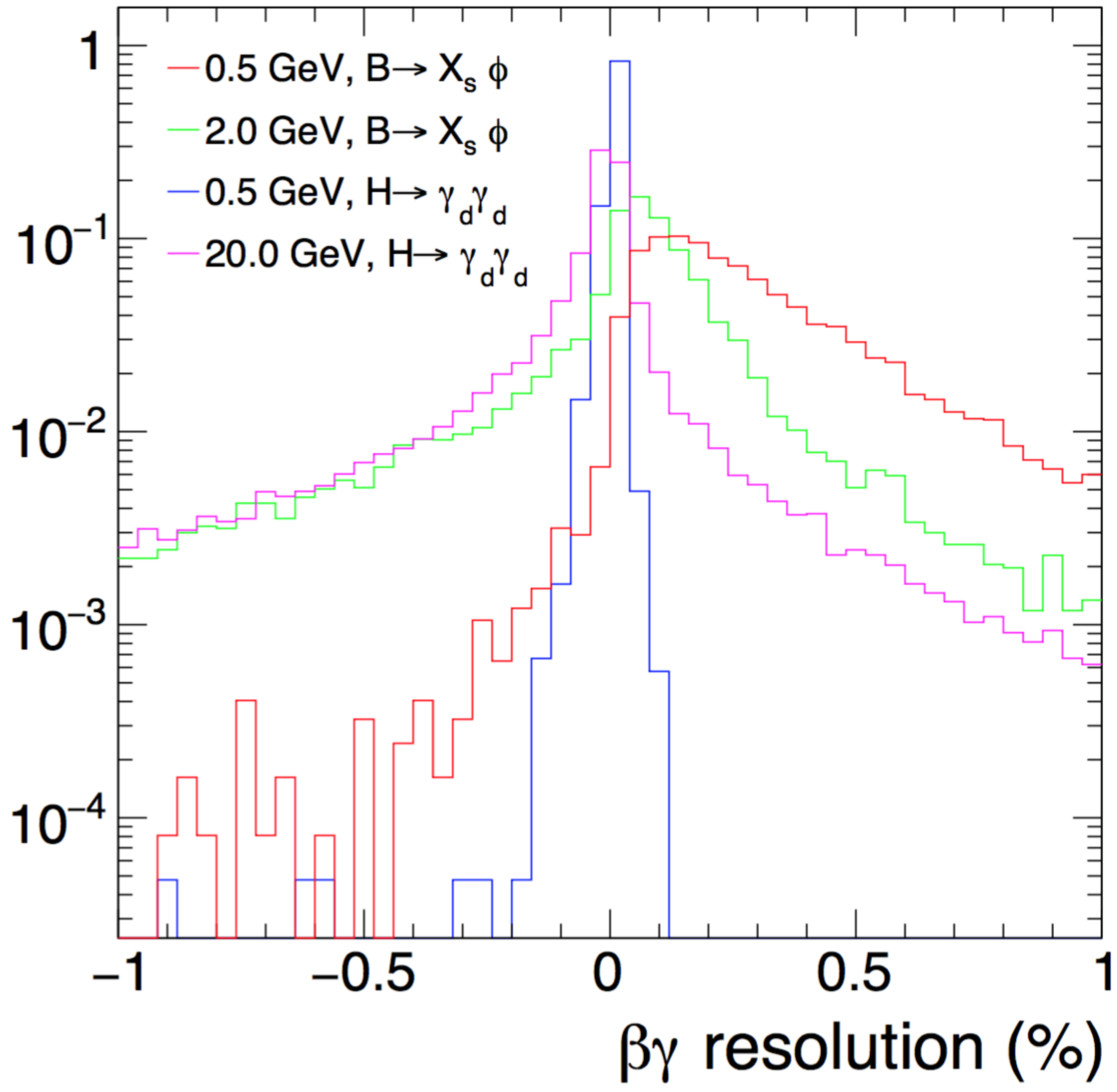
$c\tau$ (m)	m_φ $[B \to X_s\varphi]$			m_{γ_d} $[h \to \gamma_d\gamma_d]$				
	0.5	1.0	2.0	0.5	1.2	5.0	10.0	20.0
0.05	–	–	–	0.39	0.48	0.50	–	–
0.1	–	–	–	0.48	0.63	0.73	0.14	–
1.0	0.71	0.74	0.83	0.59	0.75	0.82	0.84	0.86
5.0	0.55	0.64	0.75	0.60	0.76	0.83	0.86	0.88
10.0	0.49	0.58	0.74	0.59	0.75	0.84	0.86	0.88
50.0	0.38	0.48	0.74	0.57	0.75	0.82	0.87	0.88
100.0	0.39	0.45	0.73	0.62	0.77	0.83	0.87	0.89
500.0	0.33	0.40	0.75	–	–	–	–	–

Dominated by partial overlap of decay products due to small opening angle, can be optimized using station spacing and granularity

Dominated by assumption that we don't track below 600 MeV of momentum, conservative since clearly we won't just fall off a cliff, but needs proper simulation

Bottom line : these are O(1) numbers, not O(%), can be optimized further

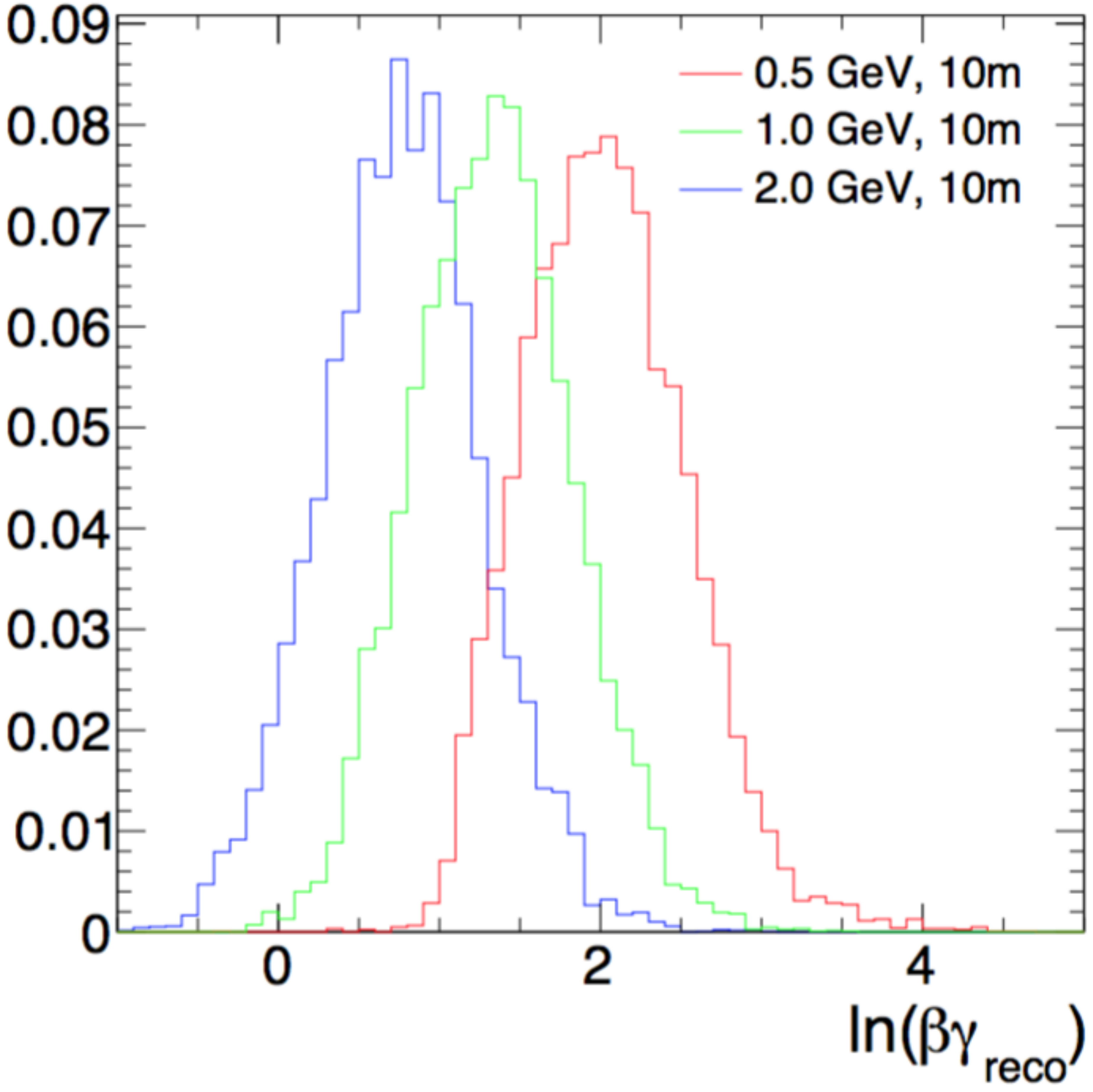
Boost reconstruction



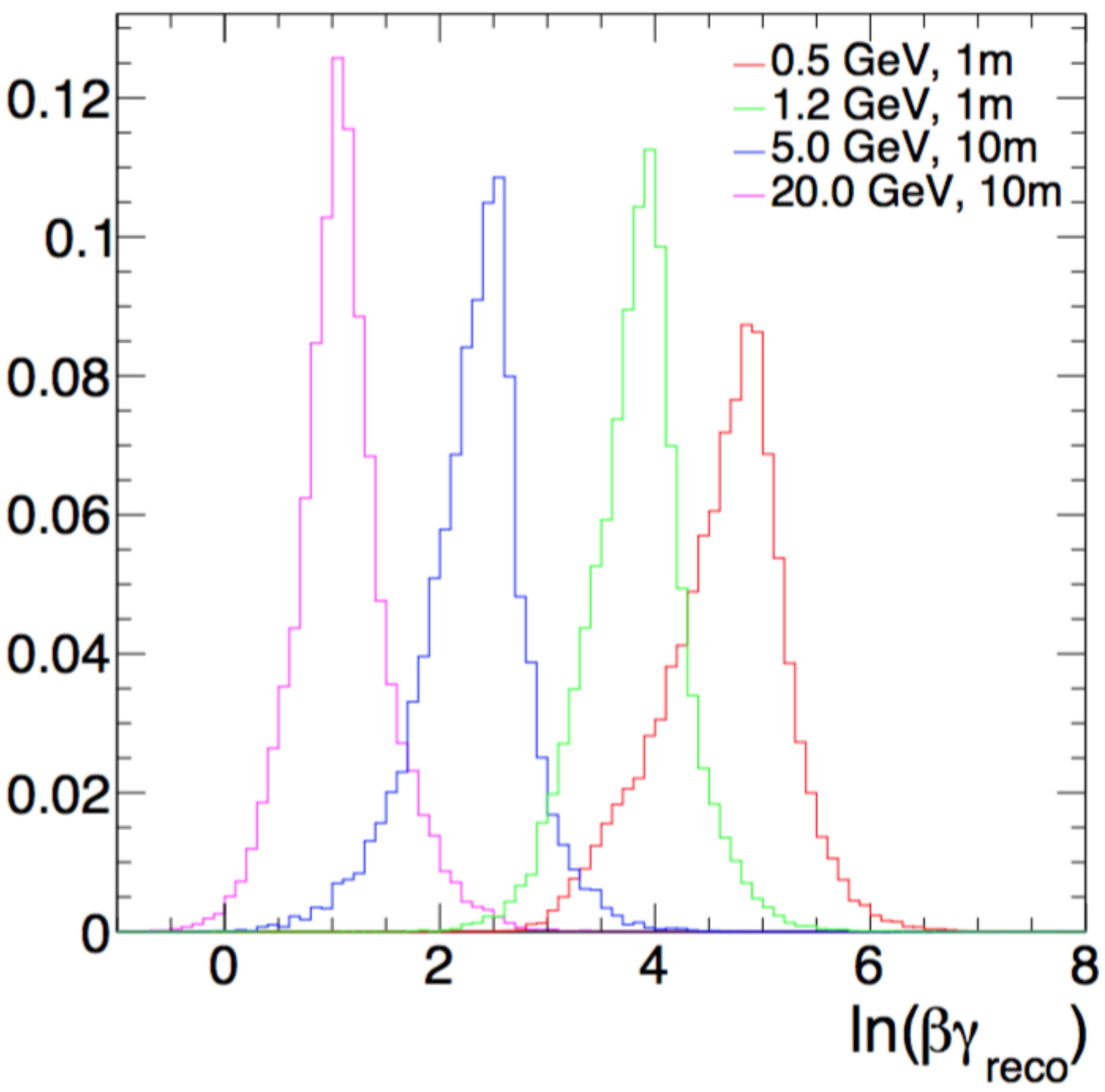
Reconstruct parent boost from the measured decay vertex (no timing!), assuming relativistic decay products. The resolution is < 1% (entirely dominated by distance to first measured point, not detector granularity) so the boost distribution is dominated by the generated spread of boosts, not resolution.

Boost reconstruction

$B \to X_s \varphi$

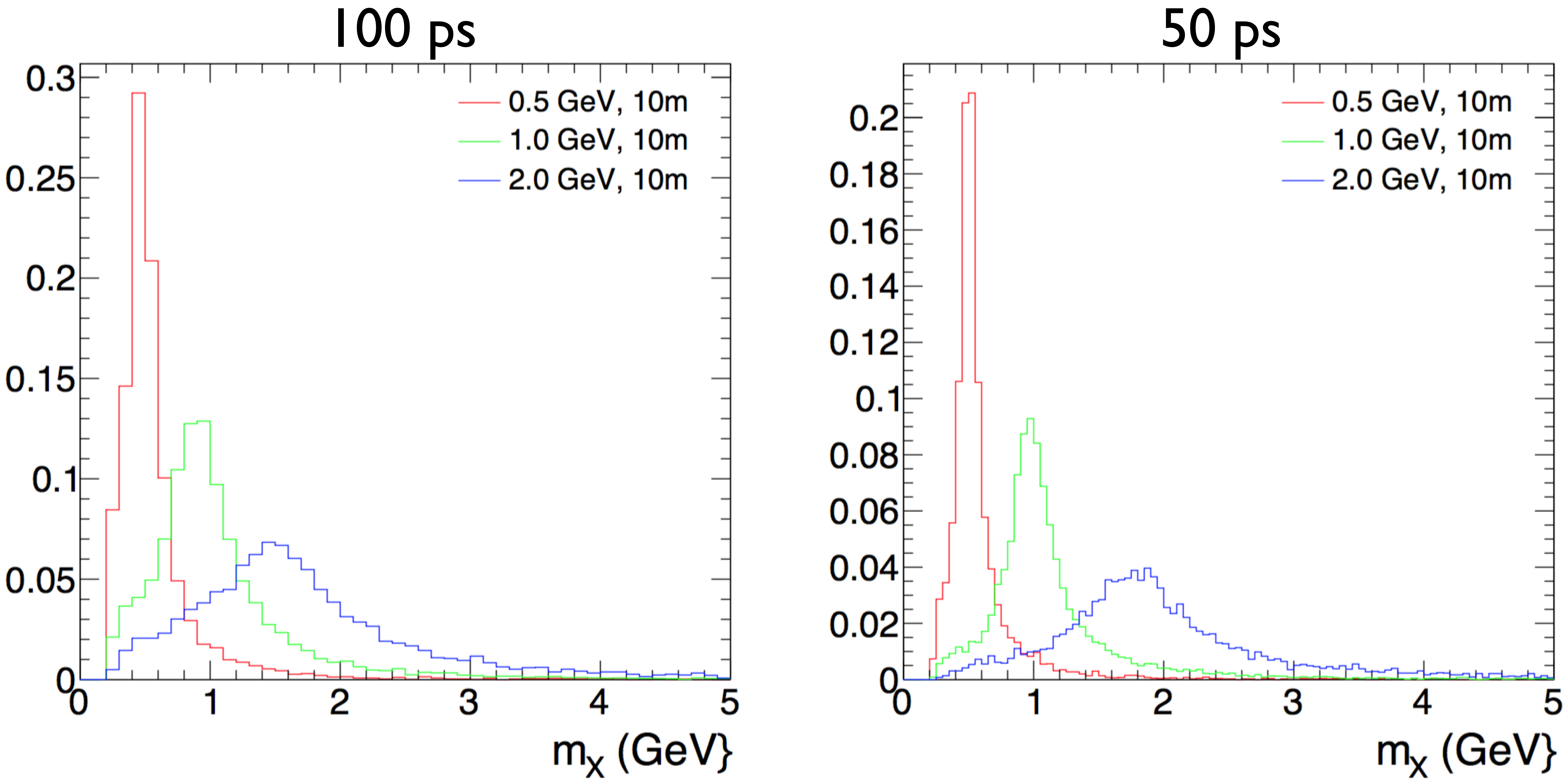


$H \to \varphi\varphi$



Different intial states give different boost distributions; perhaps surprisingly we have some discriminating power between even the B→KX scenarios.

Mass reconstruction using time-of-flight



Now assume 100/50 ps time resolution (per hit) in the tracking stations. The B→KX signals are actually slow enough that we can reconstruct the X mass…

Conclusion

Outlook for LLP searches

No theory guidance on lifetime → large detectors

Many possible decay modes → hermeticity, particle ID

Small coupling and production rate → zero background

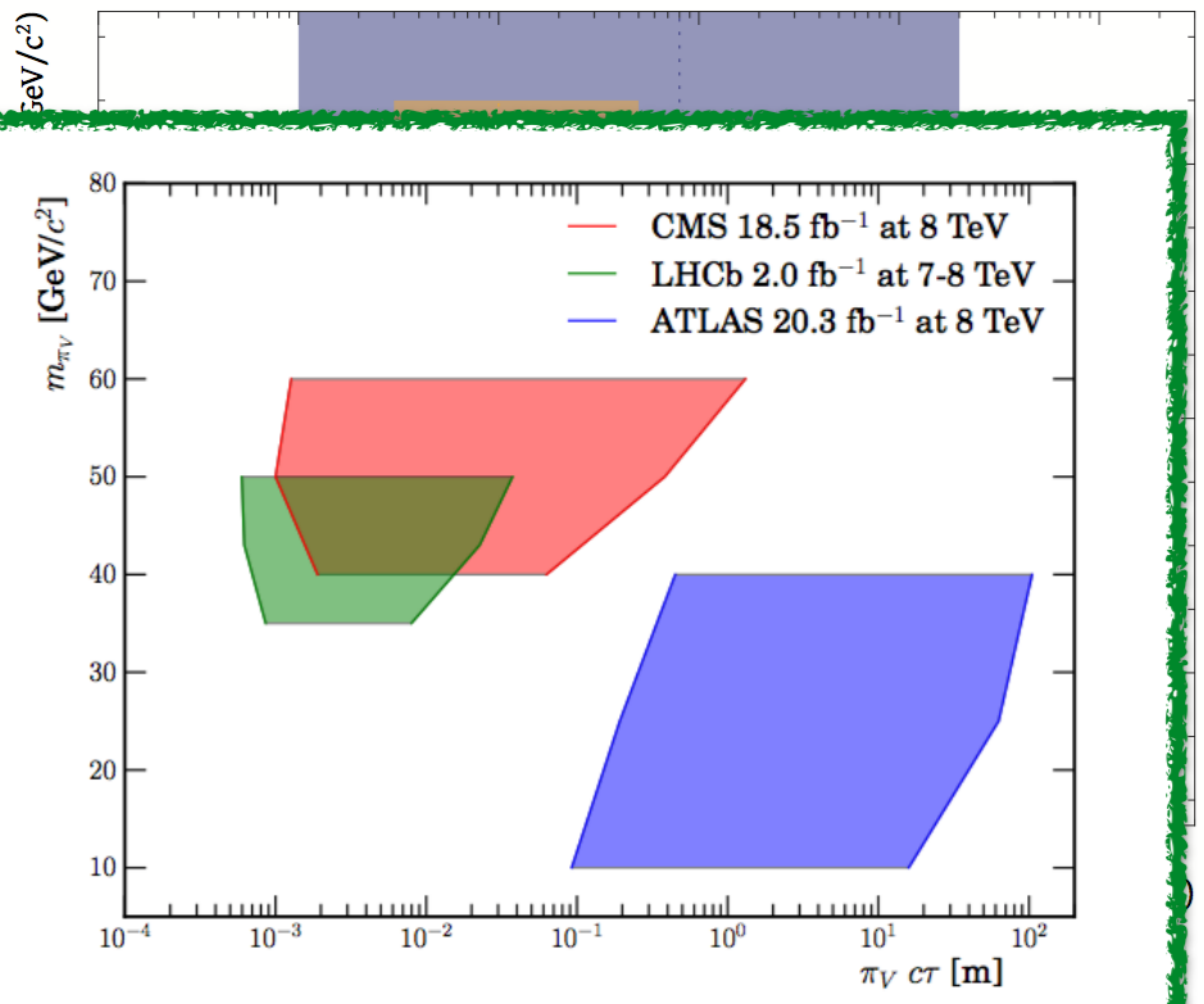
Small coupling and production rate → huge integrated lumi

Very hard for any single detector to meet all these criteria!
The proposed experiments overlap in reach but are complementary in assumptions and backgrounds — critical if signal is seen.

Backups

LHCb already complements ATLAS/CMS

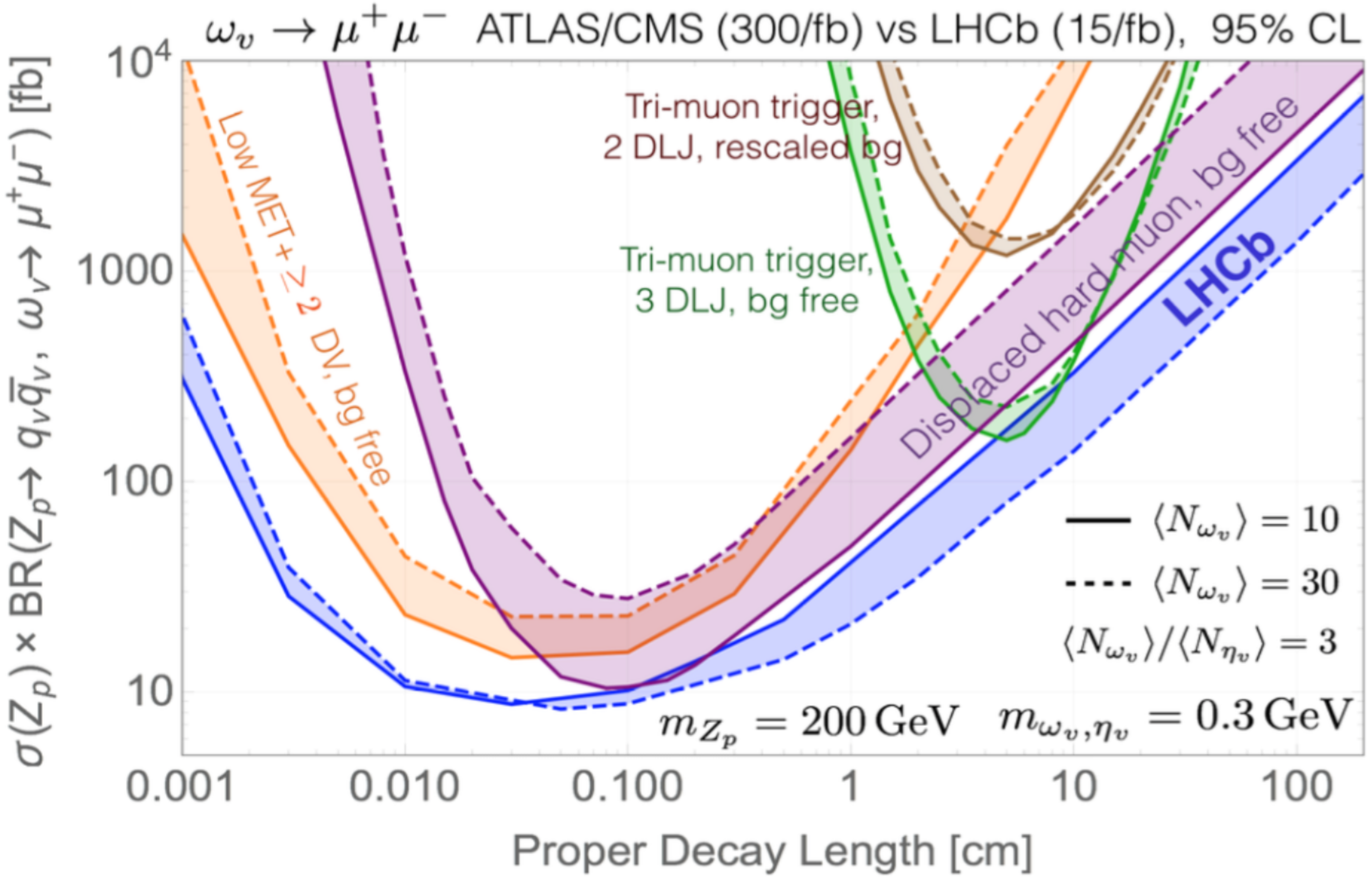
- Obvious disadvantage: LHCb collects less data than ATLAS/CMS and has worse acceptance for several searches
- But softer triggers (for instance, can trigger detached di-muons with $p_T \sim 1$ GeV/c), other advantages already mentioned
- In practice that means we can look into **complementary** phase space regions



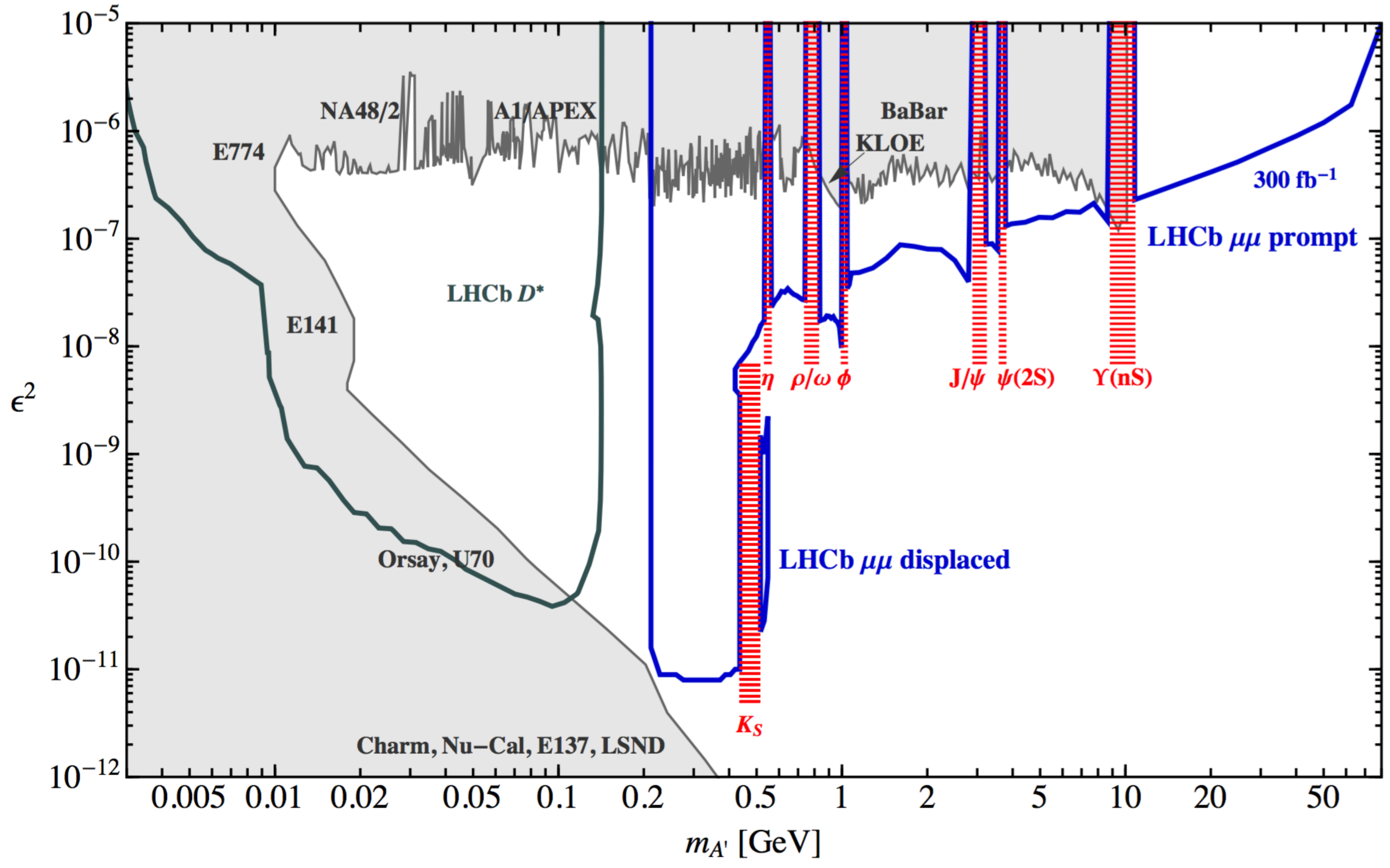
excluded areas where the limit set for H → $\pi_V\pi_V$ is smaller than 50% the SM Higgs (plot by M. Borsato)

Many thanks to Xabier for the slide from our recent HL-LHC discussions!

So is something more needed?



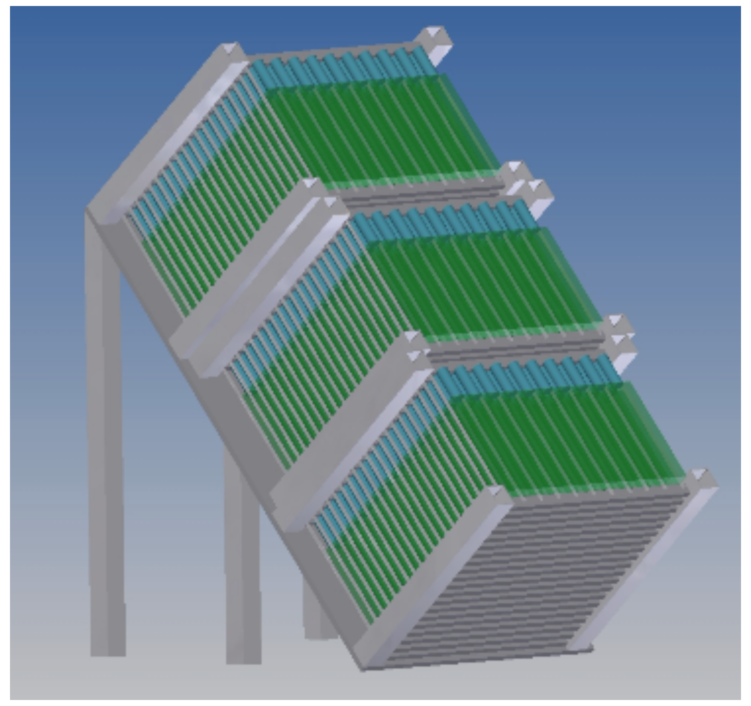
Pierce et al. https://arxiv.org/abs/1708.05389



Ilten et al.
https://arxiv.org/abs/1509.06765
https://arxiv.org/abs/1603.08926

LHCb reach worked out in certain scenarios, above showing two of them – you can see again that we can complement ATLAS/CMS for very light signals, up to a certain cτ region which is basically limited by the position of the TT where we need hits for a momentum measurement. Can we expand towards larger cτ values?

Other ideas targeting LLP’s



MilliQan: 1607.04669

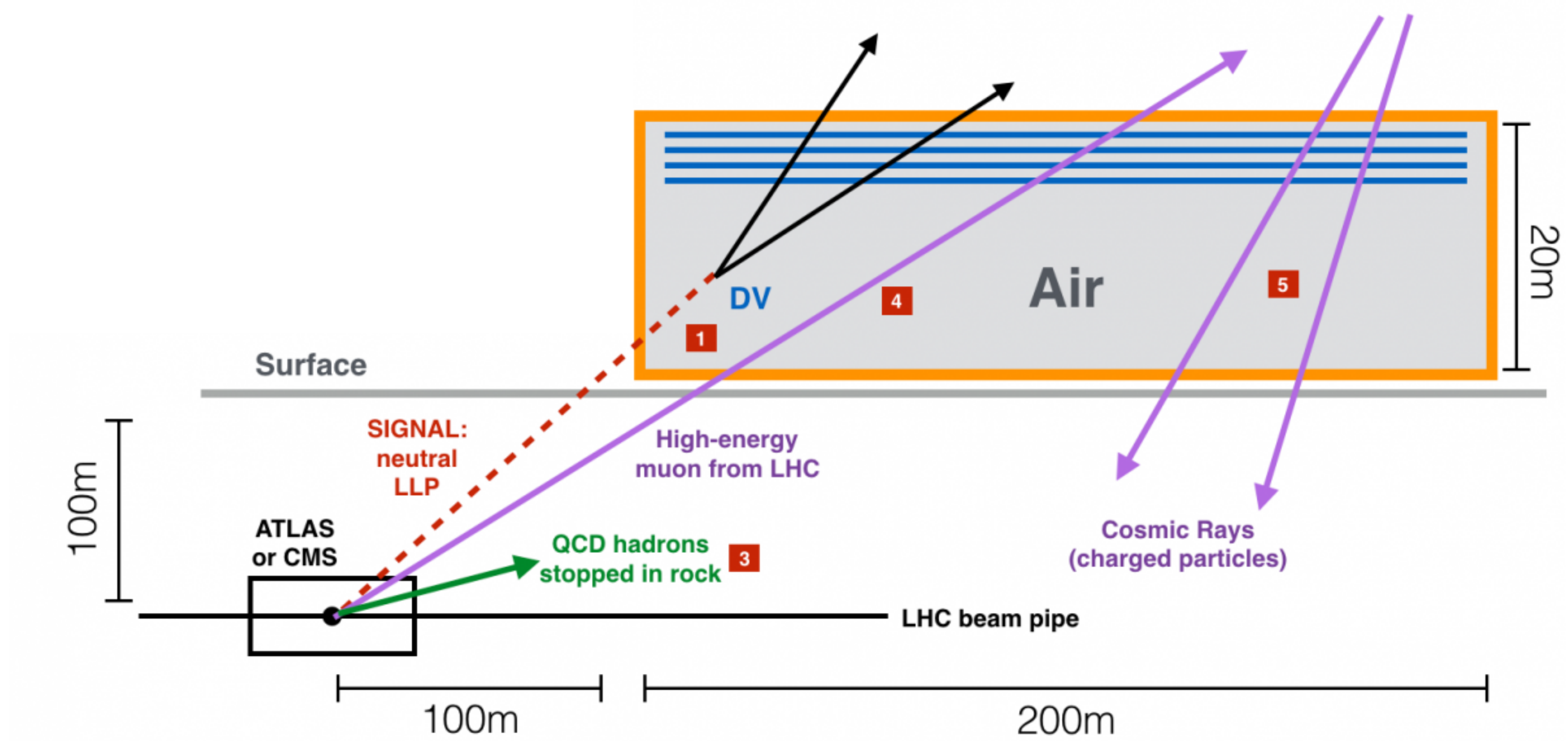
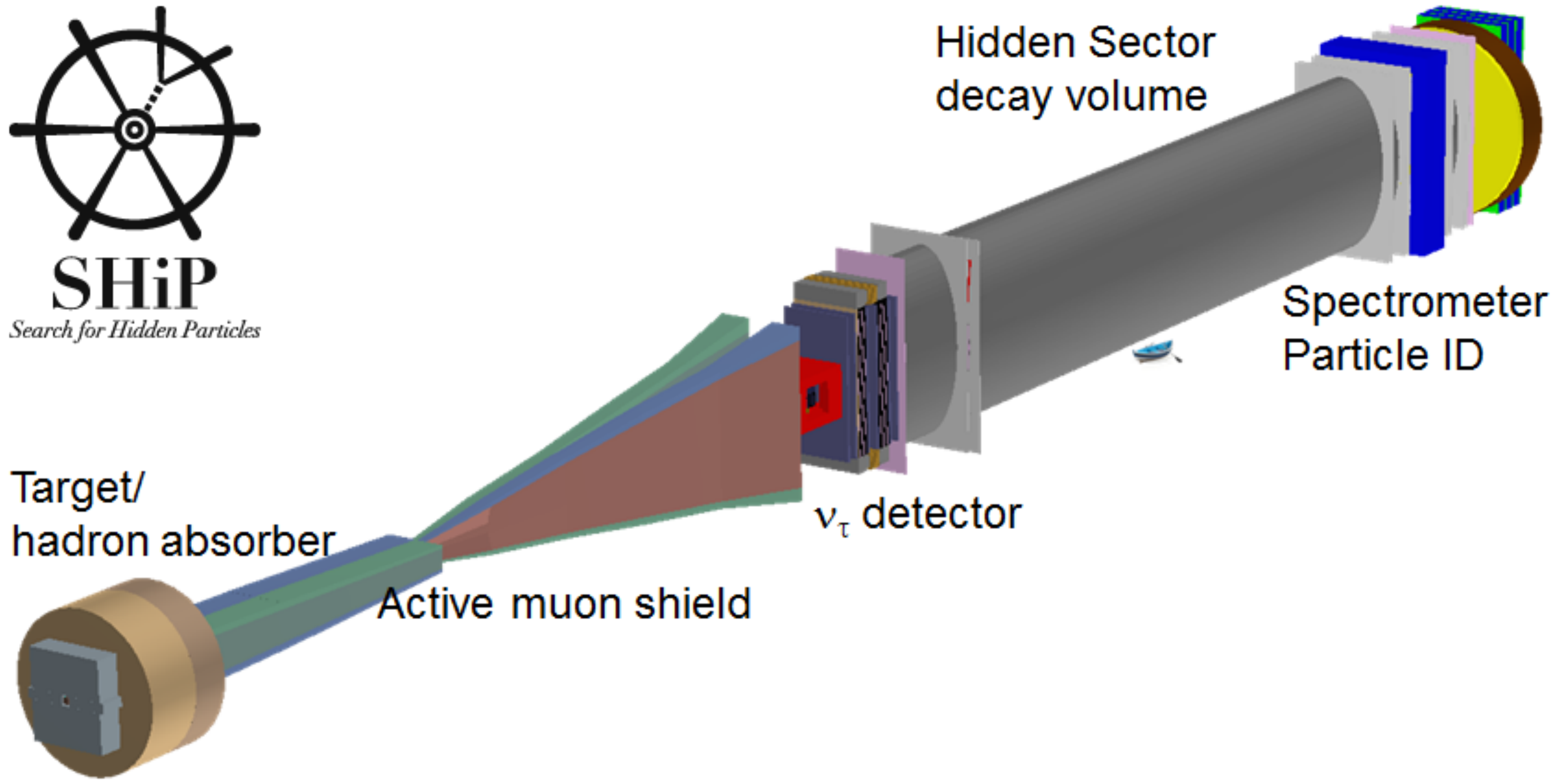
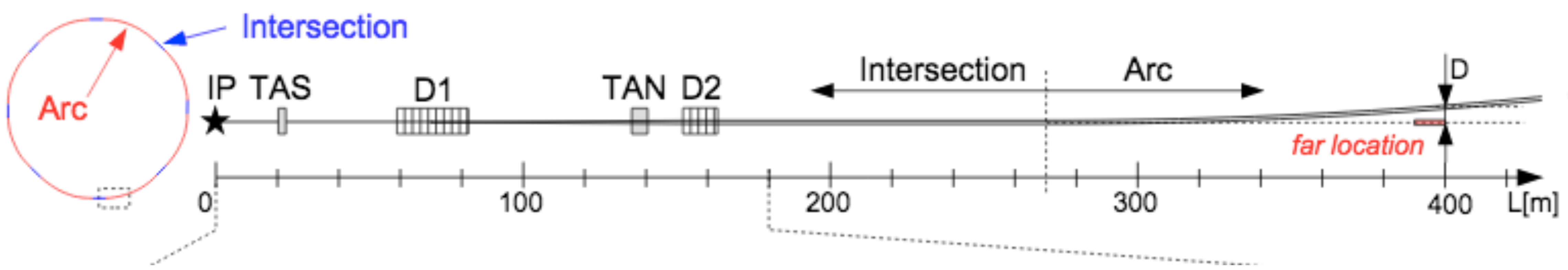


image by D. Curtin and R. Sundrum





FASER: 1708.09389

All proposals feature a substantial amount of shielding to suppress backgrounds. Useful geometric acceptance tends to require large detectors.

Integration with LHCb

It is highly desirable to treat CODEX-b as an additional subdetector of LHCb, and to integrate it into the DAQ & readout.

Allows events which look interesting in CODEX-b (whose rate is low by definition) to be saved in LHCb as well. If we see a signal we could then look at the event in LHCb and see if an interesting tag exists there.

You may think Phase II pileup would make this prohibitive, but that is not an immediate showstopper if both CODEX-b and LHCb give precise timing information.

A tricky bit is that CODEX-b "events" are offset by around ~80 ns wrt. the LHC collision which produced them, but should be manageable.

Data driven background calibration

Cosmics will be used for spatial & time detector alignment and their negligible contribution can be calibrated from this.

Other backgrounds can be measured by putting a small telescope in the LHCb cavern and measuring background rates with different shield thicknesses. Could be done as an engineering run well ahead of full detector construction.

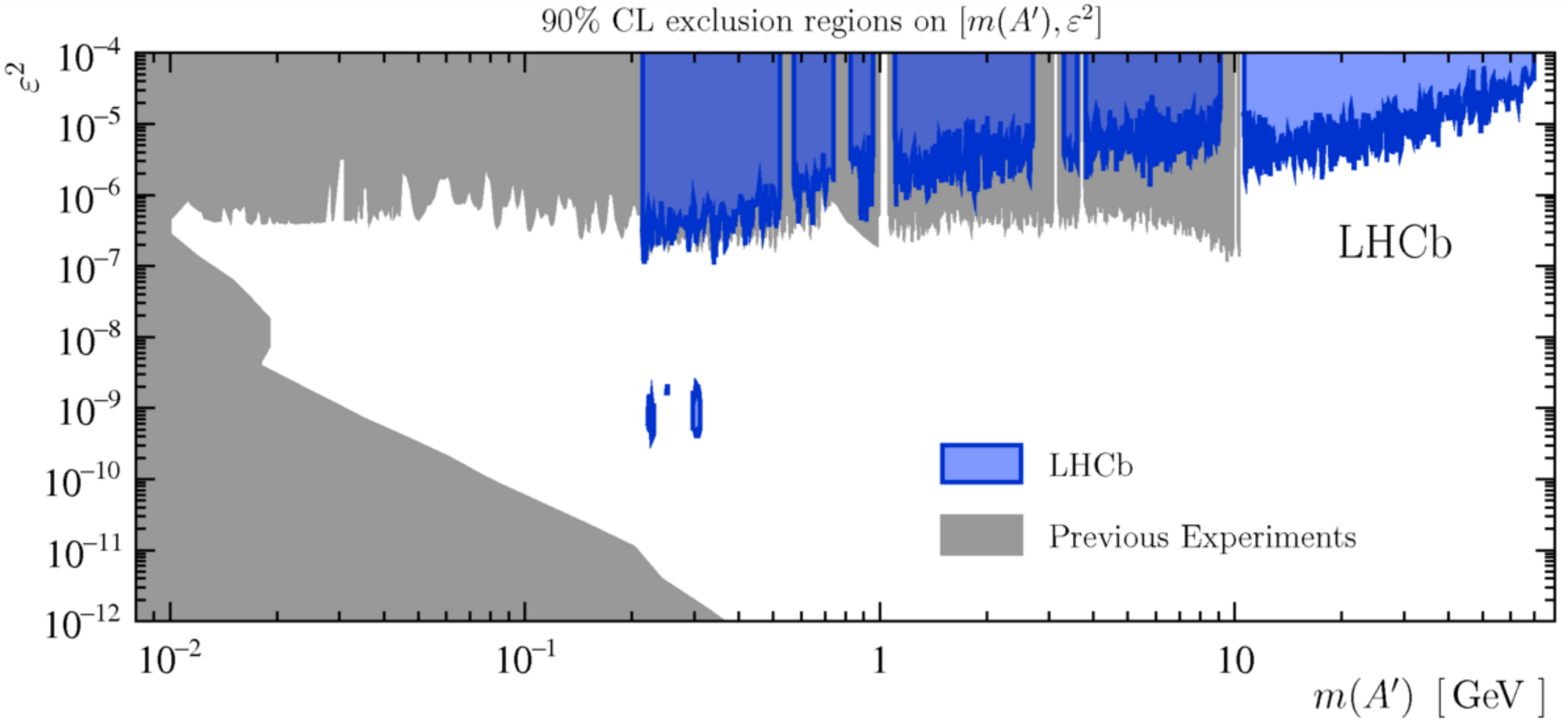
Complementarity with other searches

CODEX-b can cover a significant portion of parameter space for well-motivated, simple portals, and extend LHCb's reach for long lived particles well beyond ATLAS/CMS.

CODEX-b has to cover around 1/100th of MATHUSLA's tracking area (but of course does not have as large an absolute reach).

If you believe the physics case for LLP detection is worthwhile, allocating funds for a detector which is relatively simple to build, has complementary reach to more ambitious proposals, and has completely different backgrounds would seem prudent, particularly if someone sees a signal.

Dark photon example



The smaller the coupling, the smaller the production rate

Hence plots like this (LHCb-PAPER-2017-038) : no sensitivity to directly produced long-lived dark photons above a certain mass.